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Review

The significance of oxygen during contact lens wear

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ABSTRACT

In order to establish the relevance of oxygen to contemporary contact lens practice, a review of the literature was conducted. The results indicate that there are a number of processes occurring in the normal healthy eye where oxygen is required and which are potentially affected by the presence of a contact lens. These activities appear to take place at all corneal levels, as well as at the limbus. Evidence from laboratory, clinical and modelling studies indicates that what constitutes normal oxygenation (normoxia) depends on, among other things, the physiological system under consideration, corneal location and the state of eye closure. This diversity is reflected in the wide range of minimum lens oxygen transmissibility (Dk/t) requirements that are present in a literature.

1. Introduction

Since the discovery on the early 1950s that oxygen was necessary to prevent corneal oedema [1], it has been incumbent upon contact lens clinicians to take steps to improve the cornea's access to the atmosphere. During the early years when lenses were large, scleral and made from glass or PMMA, there was little that could be done beyond the introduction of an air bubble to the post-lens optic region. The invention of micro-corneal lenses [2] changed all that by being smaller than the cornea and mobile. So while still made from gas impermeable PMMA, these lenses allowed oxygenated tears to bathe the previously anoxic cornea. This opened the door for contact lenses to become a widely used vision correction choice. The advent of materials with intrinsic oxygen permeability, first hydrogels [3], then rigid gas permeables [4] and most recently silicone hydrogels [5], has provided an increasing range of options to help clinicians avoid the consequences of hypoxia. The last 60 years have seen considerable research conducted into the way contact lenses interact with the ocular surface, including both direct laboratory and clinical studies, as well as increasingly sophisticated modelling approaches to understanding the key physiological systems. In that time it has become evident that oxygen, or the lack of it, is an important factor determining how several systems function. An understanding of the role of oxygen in corneal health and how this is modified by contact lenses is essential to give clinicians a platform on which to base their efforts to optimize performance. The purpose of this article is to assist that process by providing a review of oxygen related interactions between contact lenses and the cornea together with its associated tissues.

We begin by considering how contact lenses may impede the eyes' access to oxygen and then move on to review the potential consequences of such interference.

2. Diffusion kinetics

There are only two routes whereby oxygen can reach the ocular surface beneath a contact lens. The first is by dissolving in the tears and passing around the lens edge into the post-lens space and the second is by diffusing through the material of the lens itself. Soft lenses have large diameters, move relatively little and closely follow the ocular surface contour, all of which limit the scope for significant tear exchange to occur [6–9]. While rigid lenses are better placed in this regard, being smaller and considerably more mobile [10], the route of oxygen supply by tear exchange has proven to be insufficient by itself to prevent clinical signs of hypoxia occurring [11]. For both rigid and soft lenses then, intrinsic oxygen permeability is a necessary requirement.

Oxygen passes through a lens by diffusion. This is passive process whereby oxygen molecules move from regions of high to low concentration in a manner that, in the steady state, is described by Fick's first law. In the case of oxygen flow through a contact lens

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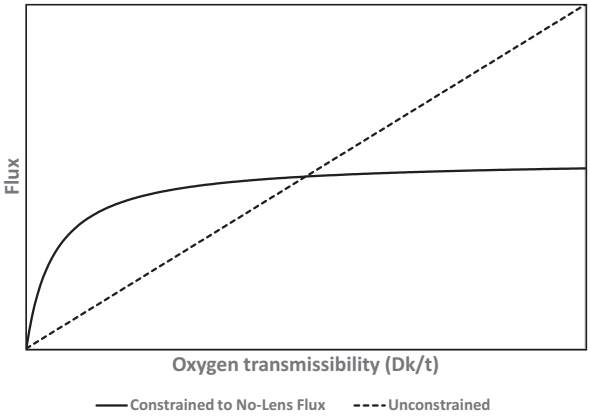

Fig. 1. Relationship between flux and oxygen transmissibility, with and without imposition of maximum permissible flux constraint.

this effectively says that the flux of oxygen molecules (J) crossing the contact lens back surface is proportional to the oxygen concentration gradient between the front and back surfaces. The constant of proportionality is the oxygen permeability of the contact lens material (Dk).

$$J = Dk\left(\frac{P_0 - P_1}{t}\right) \quad (1)$$

J = flux of oxygen crossing lens back surface, Dk = lens material oxygen permeability, P_0 = oxygen concentration at lens front surface, P_1 = oxygen concentration at lens back surface, t = lens thickness.

Associating the lens thickness (t) with the permeability term rather than the oxygen gradient, turns this into transmissibility (Dk/t).

There has been a good deal of controversy in recent years concerning the merits of transmissibility and flux as measures of contact lens oxygen performance. This competition seems odd given that both quantities are simply terms in Fick's law. Consideration of this relationship (Eq. (1)) shows two things quite clearly. First, that flux cannot be calculated unless transmissibility is known and second that we need to have values for P_0 and P_1. While it is standard practice to assume that P_0 is equivalent to a partial pressure for oxygen of 155 mmHg (atmospheric) in the open eye and 55 mmHg (posterior eyelid) in the closed eye, conditions beneath the lens are uncertain and consequently so is P_1. Therefore, establishing the actual flux into the cornea is not straightforward in most real situations.

Dk/t is widely understood and easy to measure with methods that are internationally agreed [12,13]. Nevertheless it has been criticized as a measure of contact lens oxygen delivery performance because it is a physical quantity which does not incorporate any physiological component. To understand this more clearly, return to Eq. (1) which suggests that if we attempt to approximate the non-lens wearing condition by making Dk/t increasingly large, flux through the lens continually increases and becomes infinite at infinitely high Dk/t [14]. This is shown by the broken line in Fig. 1. While this might be true for a lens in isolation, it has been seen as unrealistic for lenses on real eyes [14] because it is well known that the oxygen flux into bare human corneas is far from infinite. Literature values range between about 2 and 11 $\mu L/cm^2/h$ [15–19] with more recent measurements being at the higher end of this range [20].

To fix this problem, oxygen flux has been proposed as an alternative means of describing lens performance, with the imposed condition that its value never exceed the no-lens flux, whatever the lens transmissibility [14]. Thus, as Dk/t becomes very large, flux asymptotically approaches the no-lens level (solid line in Fig. 1) instead of going to infinity. This constraint has been incorporated into all the various models of flux that have been developed [14,18,21–23] and it should not be surprising therefore that they all show characteristic similarities of behaviour. At lower transmissibilities, flux increases rapidly as Dk/t rises but when Dk/t is already high, successive further increases necessarily produce smaller and smaller additional flux benefits – the so called "effect of diminishing returns".

Unfortunately the concept of flux as a descriptor of lens performance is not without problems of its own, mainly due to its lack of physiological uniqueness. As is evident from Fick's law, lenses with widely different transmissibilities can deliver exactly the same open eye flux if the respective post-lens oxygen tensions (PLOT) are appropriately adjusted. So at Dk/ts of 100 and 10 barrers/cm,[1] flux is identical for PLOTs of 139.5 and 0 mmHg respectively, even though these would not represent similar physiological situations. It is also possible to encounter situations where corneal metabolic activity is the same, despite there being differing fluxes [24]. The underlying issue here is that because the cornea is an oxygen permeable tissue, there is always some net diffusion across its substance, irrespective of the metabolic status of its constituent cells. Thus the oxygen flux into the cornea does not necessarily indicate the rate of consumption.

To address these difficulties, total corneal oxygen consumption rate (Q_C) has been proposed as an alternative metric [24]. Modelling of this parameter shows that it increases approximately linearly with Dk/t, up to around 15 barrers/cm in the open eye and 40 barrers/cm in the closed eye. Beyond these points the open eye curve rather abruptly flattens out to $Q_C = 4.5 \times 10^{-5}$ mL/cm^3/s at a Dk/t of 20 barrers/cm, while in the closed eye there is a more gentle asymptote to the same value at a Dk/t of 300 barrers/cm.

These estimates are somewhat lower than the 2.2×10^{-4} mL O_2/cm^3 s at 99 barrers/cm which resulted from direct measurements of Q_C made in human subjects using lenses coated on the back surface with a phosphorescent dye whose emission decay characteristics are sensitive to oxygen [25]. Perhaps of greater interest than the flux estimates themselves however is that in order to make these calculations, it is first necessary to measure PLOT. Arguably, this is one of the most relevant indices of corneal oxygenation as it forms the basis for oxygen diffusion into the cornea. The closer PLOT comes to the open eye, no-lens anterior surface value of 155 mmHg (or whatever level is typical for any given individual), the more normal corneal oxygenation would be expected to be. PLOT has been measured for a range of lenses [25,26] and those in the mid transmissibility region, around 50 barrers/cm, support levels that are about 50% of normal, sea-level, atmospheric values. Increasing this to 75% requires around 140 barrers/cm. Again, as expected the general shape of the relationship is asymptotic at high transmissibility reflecting the need for changes to be large in order to derive significant advantage in this region.

3. Tissue effects of oxygen reduction

3.1. Corneal epithelium

3.1.1. Homeostasis

As the anterior-most surface of the eye, the corneal epithelium is critically important to ocular function because it supplies both the optically smooth interface necessary for good vision and an effective defensive barrier against infection. Being a regenerative

[1] The barrer/cm unit of transmissibility is equivalent to 1×10^{-9} (cm/s) (mL O_2/mL/mm Hg). Stern SA. The "barrer" permeability unit. Journal of Polymer Science Part A-2: Polymer Physics 1968;6(11):1933–1934.