# OXYGEN LEVELS AND OXYGEN FLUX WITH SILICONE HYDROGEL CONTACT LENSES UNDER OPEN AND CLOSED EYE CONDITIONS


**Percy Lazon de la Jara[1], Brien Holden[1,2,3], Robert Terry[1], Donna La Hood[1], Klaus Ehrmann[1,2]**

[1]Institute for Eye Research, Sydney Australia, [2]Vision Cooperative Research Centre, Sydney, Australia, [3]School of Optometry and Vision Science, UNSW, Sydney, Australia


## INTRODUCTION

- A high level of oxygen in the pre-corneal tear film during contact lens wear is required to prevent structural and physiological changes associated with hypoxia[1]. Adverse effects occur with greater frequency and severity when the partial pressure of oxygen ($P_0$) behind the contact lens is low[2, 3].
- The minimum atmospheric oxygen requirements to prevent corneal effects include:
  - Corneal oedema 10% oxygen[1,4]
  - Loss of sensitivity 8% oxygen[5]
  - Reduction in corneal mitosis 13% oxygen[6]
  - Peripheral corneal edema 12% oxygen[4]
  - Endothelial blebs 16.6% oxygen[7]
  - Limbal Redness 16.8% oxygen[8]
  - Epithelium acidosis 20.9% oxygen[9]
- In this study Equivalent Oxygen Percentage (EOP), oxygen partial pressure under a lens ($P_0$) and oxygen flux into the eye during contact lens wear were calculated by measuring oxygen uptake rates (OUR) into the lens front surface in vivo[10] or into the cornea after contact lens wear[11] under open and closed eye conditions.

## AIMS

- To determine the EOP with various silicone hydrogel and control hydrogel contact lenses under open and closed eye conditions.
- To derive $P_0$ and oxygen flux during contact lens wear under open eye conditions.

## MATERIALS & METHODS

- Ten non-habitual contact lens wearers wore all lenses in a prospective, non-dispensing, randomised, open label study.
- Four silicone hydrogel lens materials (Focus NIGHT & DAY, $O_2$Optix, PureVision and Acuvue Advance) in two lens powers (-3.00DS and +6.00DS); one conventional 58% water content hydrogel (Acuvue 2, -3.00DS) and a thicker conventional 38% water content hydrogel (CIBASoft, +6.00D) were used.
- The Dk of each lens material and central and harmonic mean thicknesses (t) for the central 8 mm of each lens and power were measured. Dk/t was calculated using these measured values.
- The Clark-type polarographic oxygen sensor (POS) Radiometer E5047/0 and Radiometer Amplifier PHM 73 linked to a personal computer were used to measure oxygen uptake rates (OUR) into the contact lens or into the cornea.
- The polarographic oxygen sensor (POS) was calibrated in air (155 mmHg O2) and nitrogen (0 mmHg $O_2$) in saturated Milli-Q solution maintained at 36°C at each session. The 140-40 mm Hg segments of the POS-reservoir depletion records were recorded and used to derive the OUR.
- Baseline corneal oxygen uptake rates (COURs) were measured by placing the polarographic oxygen sensor on the corneal surface and measuring the rate of flow of oxygen out of the sensor into the cornea of each of the subjects. Three baseline readings were taken for each eye.
- Contact lens oxygen uptake rates (CLOURs) on the surface of the contact lens were measured after 30 minutes contact lens wear under open eye conditions.
- Equivalent Oxygen Percentages (EOPs) were obtained by comparing COURs immediately after the contact lens was slid off (average 1.5 secs) following 45 minutes of contact lens wear under open eye conditions to those obtained with a series of six known gases in goggles (0%, 5.5%, 10.2%, 15.0%, 18.0%, 21.0% oxygen concentration) on the same subjects.
- Closed eye EOPs were measured using COURs obtained immediately after the eye was opened and the lens was slid off (average 3 secs) following 5 minutes of contact lens wear under closed eye conditions.
- Mathematical models were developed to calculate $P_0$ and oxygen flux using the contact lens oxygen uptake rate (mmHg/s) under open eye conditions following Rasson and Fatt as follows:
  - When the probe is applied to a lens front surface an immediate fall in $pO_2$ is recorded on the front of the lens but this decrease takes some time to be felt at the back of the lens; the time taken determined which model was applicable. Such models depend on the square of thickness and diffusion coefficient ($l^2/D$). This property represents how quickly a change in conditions at the front of the lens is experienced at the back of the lens.
  - It was assumed that before the probe is applied on the lens, oxygen levels in the lens and eye are in equilibrium and Fick's Second Law applies.
  - Other assumptions included that the corneal oxygen consumption rate and the lens centre thickness were constant during the measurement period. The solubility of oxygen in silicone (i.e. polymethydisiloxane - PDMS) and water and the percentages of these two components in each lens were used to estimate oxygen solubility (k) in each lens material.The diffusion coefficient for each material was derived from the weighted k of PDMS for each lens.
- The equilibrium oxygen flux for each lens material was expressed in terms of a relative oxygen flux scale; where 1 equals the derived oxygen flux through the highest central Dk/t lens.

## RESULTS

### PARTIAL PRESSURE OF OXYGEN BEHIND SILICONE HYDROGELS UNDER OPEN EYE CONDITIONS CALCULATED FROM CONTACT LENS OXYGEN UPTAKE RATES

- $P_0$ (mmHg) increased with increasing contact lens Dk/t (Figure1). Significant differences in $P_0$ occurred between silicone hydrogel lenses (Tables 1 and 2)
- The following non-linear regression equation was fitted to derive the relationship between central Dk/t and $P_0$ using the mean values for each lens type and power as shown in Figure 1.

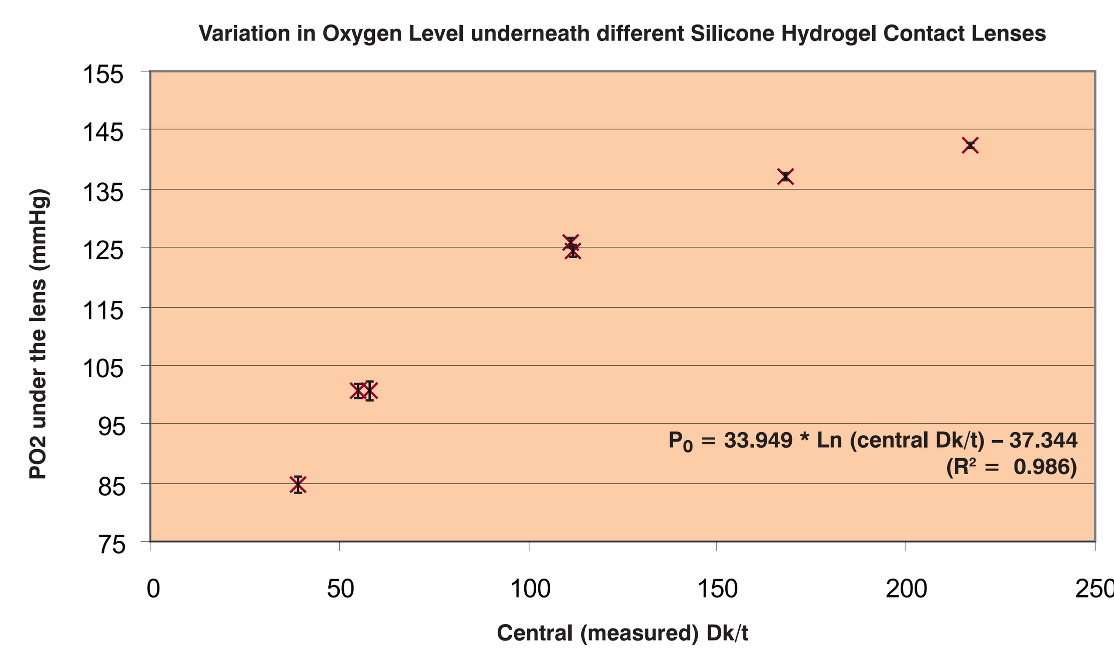


*Figure 1. Calculated $P_0$ underneath lenses under open eye conditions. Each data point represents the mean CLOUR for 10 subjects with each lens and the error bars the standard error of the mean for the lens type.*

Table 1. Significant differences in $P_0$ between -3.00D silicone hydrogel lenses under open eye conditions.

| $P_0$ Between -3.00D Si-Hi | | | | | | Linear Mixed Model ANOVA | Post Hoc Bonferroni Comparison | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Lens Group | N | Mean | SD | Min | Max | | Advance | FND | $O_2$Optix | PV |
| Focus N&D -3.00 | 10 | 142.5 | 1.1 | 141.2 | 144.9 | <0.001 | <0.001 | | <0.001 | <0.001 |
| $O_2$Optix -3.00 | 10 | 137.2 | 1.6 | 134.2 | 139.3 | | <0.001 | <0.001 | | <0.001 |
| PureVision -3.00 | 10 | 125.9 | 2.3 | 122.0 | 129.0 | | 0.236 | <0.001 | <0.001 | |
| Advance -3.00 | 10 | 124.4 | 3.0 | 118.5 | 127.9 | | | <0.001 | <0.001 | 0.236 |

### RELATIVE OXYGEN FLUX INTO THE CORNEA WITH DIFFERENT SILICONE HYDROGELS AND THICK HEMA CONTACT LENS UNDER OPEN EYE CONDITIONS

- The relative oxygen flux increased to 1.36 units with increasing Dk/t up to 84 units and then fell to 1 with the highest Dk/t lens as shown in Figure 2.

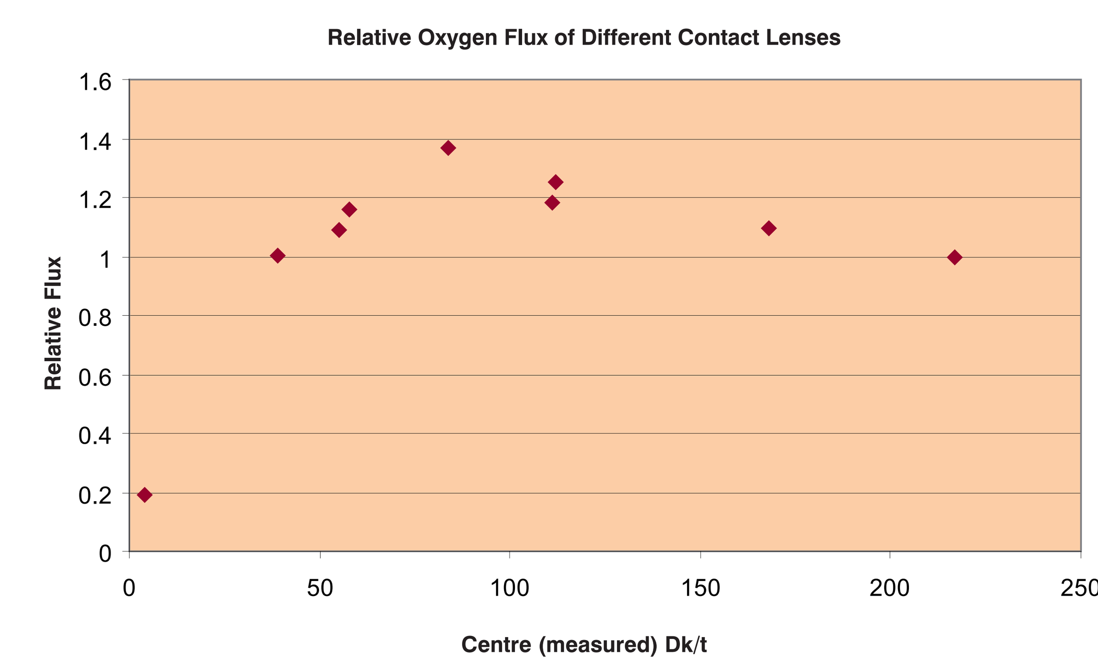


*Figure 2. Relative oxygen flux versus central average Dk/t for different silicone hydrogels and a thick HEMA. Each data point represents the relative mean of 10 subjects for each lens.*

Table 2. Significant differences in $P_0$ between +6.00D silicone hydrogel lenses under open eye conditions.

| $P_0$ Between +6.00D Si-Hi | | | | | | Linear Mixed Model ANOVA | Post Hoc Bonferroni Comparison | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Lens Group | N | Mean | SD | Min | Max | | Advance | FND | $O_2$Optix | PV |
| Focus N&D +6.00 | 10 | 110.5 | 2.3 | 107.3 | 114.0 | <0.001 | <0.001 | | <0.001 | <0.001 |
| $O_2$Optix +6.00 | 10 | 100.7 | 5.1 | 89.5 | 107.9 | | <0.001 | <0.001 | | 1.000 |
| PureVision +6.00 | 10 | 100.7 | 3.8 | 92.1 | 106.7 | | <0.001 | <0.001 | 1.000 | |
| Advance +6.00 | 10 | 84.7 | 4.2 | 79.6 | 93.9 | | | <0.001 | <0.001 | <0.001 |

### EQUIVALENT OXYGEN PERCENTAGE (EOP)

#### OPEN EYE CONDITIONS

- The relationship between EOP under open eye conditions and Dk/t (averaged over the central 8 mm) is shown in Figure 3.

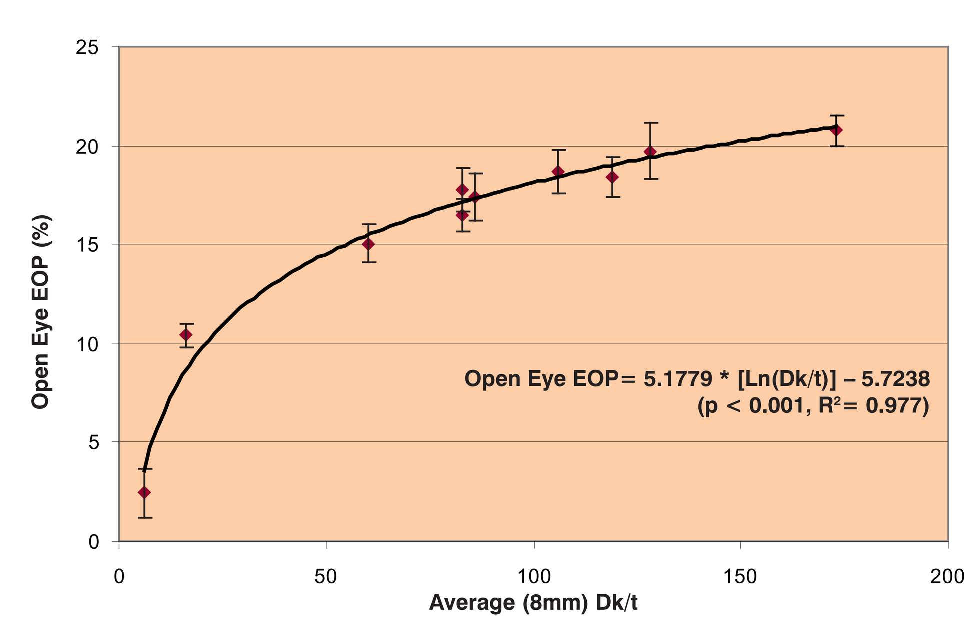


*Figure 3. Each data point represents the mean EOP of 10 subjects for each lens. The error bars are derived from the standard error of the mean.*

- The EOPs values for lenses with an average (central 8 mm) Dk/t lower than 83 were statistically different from those above 106. Moreover, lenses with an average Dk/t of 174 were statistically different from lenses with a lower average Dk/t of 128, as shown in table 3.

Table 3. EOP values estimated for the different lens types under open eye conditions

| Average Dk/t (8mm) | 6 | 16 | 40 | 60 | 83 | 106 | 119 | 128 | 174 |
|---|---|---|---|---|---|---|---|---|---|
| Estimated EOP Open Eye | 3.6 | 8.6 | 13.4 | 15.5 | 17.2 | 18.4 | 19.0 | 19.4 | 21.0 |
| EOP Lower 95% CI | 2.2 | 7.7 | 12.8 | 14.9 | 16.6 | 17.8 | 18.4 | 18.7 | 20.2 |
| EOP Upper 95% CI | 4.9 | 9.5 | 14 | 16.0 | 17.7 | 19.0 | 19.7 | 20.1 | 21.8 |

#### CLOSED EYE CONDITIONS

- The relation between EOP under closed eye conditions and Dk/t (averaged over the central 8 mm) is shown in Figure 4.

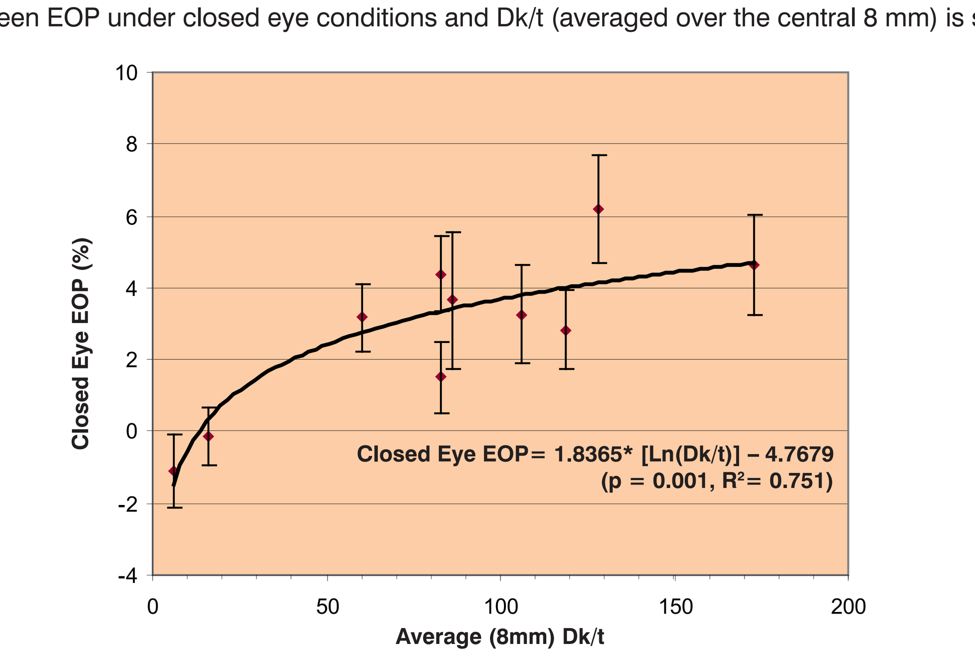


*Figure 4. Each data point represents the mean EOP of 10 subjects for each lens. The error bars are derived from the standard error of the mean.*

- The EOPs values for lenses with an average (central 8 mm) Dk/t lower than 40 were statistically different from those above 106 as shown in table 4.

Table 4. EOP values estimated for the population under closed eye conditions for different Dk/t's.

| Average Dk/t (8mm) | 6 | 16 | 40 | 60 | 83 | 106 | 119 | 128 | 174 |
|---|---|---|---|---|---|---|---|---|---|
| Estimated EOP Closed Eye | -1.5 | 0.3 | 2.01 | 2.8 | 3.3 | 3.8 | 4.0 | 4.1 | 4.7 |
| EOP Lower 95% CI | -3.3 | -0.9 | 1.21 | 2.0 | 2.6 | 3.0 | 3.1 | 3.2 | 3.7 |
| EOP Upper 95% CI | 0.4 | 1.6 | 2.8 | 3.5 | 4.1 | 4.6 | 4.9 | 5.0 | 5.7 |

## STATISTICAL ANALYSIS

- Non-linear regressions were conducted to determine the relationships between $P_0$ behind the lenses, (relative) oxygen flux and EOP, with Dk/t.
- Linear Mixed Model ANOVAs were used to compare P0 behind the lenses. Bonferroni post-hoc comparisons were used for paired comparisons. The critical level for statistical significance was $p < 0.05$, with adjustment for multiple comparisons.

## CONCLUSIONS

- As Dk/t increases, the availability of oxygen underneath the contact lens increases in a logarithmic manner.
- Significant differences in oxygen level underneath lenses ($P_0$ and EOP) occurred between conventional hydrogel lens and silicone hydrogel lenses, and between lower and higher Dk/t silicone hydrogel lenses.
- Relative oxygen flux was unable to differentiate between the corneal oxygenation levels under contact lenses of low and high Dk/t.
- Deriving $P_0$ from the CLOUR and measurements of lens Dk and thickness and estimates of $P_1$, D and k gave less variable results than EOP, due presumably to the more interventionist nature of the EOP measurement method.
- Limitations of this study include:
  - Dynamic measurements on-eye disrupt the steady-state.
  - Assumption that the solubility of oxygen in the silicone hydrogel 'backbone' is the same as PDMS.
- Further research and refinement of the models including the parameters of the lenses such as D and k for each material will give better definitions of $P_0$ and oxygen flux.

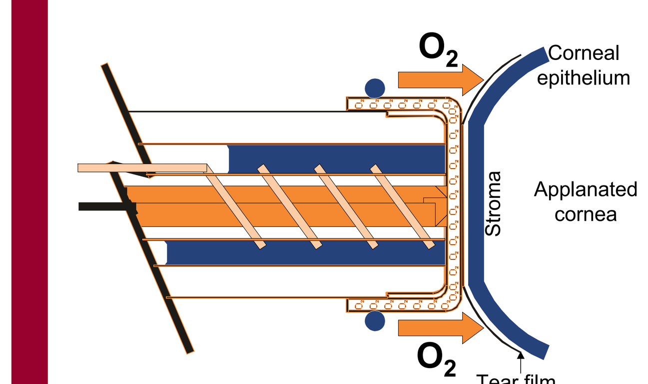


*Figure 5. Oxygen Sensor at Applanation*

*Figure 6. Oxygen Sensor Applanating bare cornea*

## ACKNOWLEDGMENTS


We thank Geoffrey Brent and Simon Evans for their contributions to development of the mathematical models. This study was funded in part by the Australian Federal Government through the CRC scheme, the Institute for Eye Research and by CIBA Vision.


## REFERENCES


1. Holden BA, Sweeney DF, Sanderson G. The minimum precorneal oxygen tension to avoid corneal edema. Invest Ophthalmol Vis Sci 1984;25(4):476-80.
2. Bonanno JA, Polse KA. Corneal acidosis during contact lens wear: effects of hypoxia and CO2. Invest Ophthalmol Vis Sci 1987;28(9):1514-20.
3. McNamara NA, Chan JS, Han SC, Polse KA, McKenney CD. Effects of hypoxia on corneal epithelial permeability. Am J Ophthalmol 1999;127(2):153-7.
4. Brennan NA, Efron N, Carney LG. Critical oxygen requirements to avoid oedema of the central and peripheral cornea. Acta Ophthalmol (Copenh) 1987;65(5):556-64.
5. Millodot M, O'Leary DJ. Effect of oxygen deprivation on corneal sensitivity. Acta Ophthalmol (Copenh) 1980;58(3): 434-9.
6. Hamano H, Hori M, Hamano T, Kawabe H, Mikami M, Mitsunaga S, Hamano T. Effects of contact lens wear on mitosis of corneal epithelium and lactate content in aqueous humor of rabbit. Jpn J Ophthalmol 1983;27(3):451-8.
7. Williams L. Transient endothelial changes in the in vivo human cornea. Sydney: University of New South Wales; 1986.
8. Papas E. On the relationship between soft contact lens oxygen transmissibility and induced limbal hyperaemia. Exp Eye Res 1998;67(2):125-31.
9. Giasson C, Bonanno JA. Corneal epithelial and aqueous humor acidification during in vivo contact lens wear in rabbits. Invest Ophthalmol Vis Sci 1994;35(3):851-61.
10. Rasson JE, Fatt I. Oxygen flux through a soft contact lens on the eye. Am J Optom Physiol Opt 1982;59(3):203-12.
11. Hill RM, Fatt I. Oxygen Uptake from a Reservoir of Limited Volume by the Human Cornea in Vivo. Science 1963;142: 1295-7.


VISION EXCELLENCE FOR ALL PEOPLE