

Gaussian Optics Analysis for human Eyes with Application for Vision Corrections

ABSTRACT

Aims: To analyze the roles of ocular components of human eye on the refractive power in various applications.

Study design: Gaussian optics analysis.

Place and Duration of Study: Taipei, Taiwan, between May 2015 and August 2016.

Methodology: An effective eye model is introduced by the ocular components of human eye including refractive indexes, surface radius (r_1 , r_2 , R_1 , R_2) and thickness (t , T) of the cornea and lens, the anterior chamber depth (S_1) and the vitreous length (S_2). Gaussian optics is used to calculate the change rate of refractive error per unit amount of ocular components of a human eye.

Results: For typical corneal and lens power of 42 and 21.9 diopters, the rate function M_j ($j=1$ to 6) are calculated for a 1% change of r_1 , r_2 , R_1 , R_2 , t , T (in diopters) $M_1=+0.485$, $M_2=-0.063$, $M_3=+0.053$, $M_4=+0.091$, $M_5=+0.012$, and $M_6=-0.021$ diopters. For 1.0 mm increase of S_1 and S_2 , the rate functions are: $M_7=+1.35$, and $M_8=-2.67$ diopter/mm.

Conclusion: Using Gaussian optics, we have derived analytic formulas for the change of refractive power due to various ocular parameter changes. These formulas provide the amount of refractive error corrections in various applications including laser in situ keratomileusis (LASIK) surgery, corneal cross linking (CXL) procedure, femtosecond laser surgery and scleral ablation for accommodation.

Keywords: [Gaussian optics, human eye, ocular components, refractive errors, vision correction]

1. INTRODUCTION

Gaussian optics [1,2] has been used for the calculations of intraocular lens (IOL) power, accommodation amplitude in IOL and human natural lens and the refractive state of human eyes [1-6]. A complete optical description of a human eye should include its 12 ocular parameters, 4 refractive indexes, 4 surface radius and 2 thickness (for cornea and lens), the anterior chamber depth and the vitreous length (or axial length). The roles of these parameters on the refractive power of an eye have been reported only partially [2,3]. This study will derive analytic formulas for the change rate of refractive error per unit amount of selected ocular components.

Base on an effective eye model, a new standard for refractive state is governed by the relative axial length of ($L-L^*$), rather than its absolute axial length (L), where L^* is the axial length of the emmetropic state. A conversion function defined by the ratio between the refractive error change and the lens power change is used to calculate the rate functions. The roles of the surface radius of the cornea and lens on the refractive error, the competing factors of anterior chamber depth (resulting in hyperopia shift) and posterior chamber depth (resulting in myopia shift) are discussed. Finally, various new applications related to the formulas developed in this paper including laser in situ keratomileusis (LASIK) surgery, corneal cross linking (CXL) procedure, femtosecond laser surgery and laser scleral ablation for accommodation will be presented. The analytic formulas developed in this paper provide useful clinical guidance for vision corrections in various applications.

2. MATERIAL AND METHODS

2.1 The Effective Eye Model

By Gaussian optics theory (or paraxial ray approximation along the axial axis), the refractive error (De) as a function of the system effective focal length (EFL) (F), axial length (L) and position of the system second principal plane ($L2$) as follow [1,2]

$$De = 1000 [n1/(L-L2) - n1/F], \quad (1)$$

where $n1$ is the refractive index of the aqueous humor. F is the system EFL defines the system total power $D=1000n1/F$ (D in diopter, F in mm) which is determined by the corneal ($D1$) and lens power ($D2$) as follows [2,3]

$$D = D1 + D2 - S(D1D2)/(1000n1), \quad (2.a)$$

$$D1 = 1000 [(n3-1)/r1 - (n3-n1)/r2] + bt, \quad (2.b)$$

$$D2 = 1000 [(n4-n1)/R1 + (n4-n2)/R2] - aT, \quad (2.c)$$

where n_j ($j=1, 2, 3, 4$) are the refractive index for the aqueous, vitreous, cornea and lens, respectively. The anterior and posterior radius of curvatures (in the unit of mm) of the cornea and lens are given by ($r1$, $r2$) and ($R1$, $R2$), respectively, where the only concave surface $R2$ is taken as its absolute value in this study. Finally, S is the effective anterior chamber depth, related to the anterior chamber depth (ACD), $S1$, by $S=S1+P11+0.05$ (in mm), where $P11$ is the distance between the lens anterior surface and its first principal plane, and 0.05 mm is a correction amount to include the effect of corneal thickness (assumed to be 0.55 mm) [2,3]. The thickness terms in Eq.(2.b) and (2.c) are given by $b=11.3/(r1r2)$, $a=4.97/(R1R2)$ for refractive indexes of $n1 = n2 = 1.336$, $n3 = 1.377$ and $n4 = 1.42$; and t and T are the thickness of the cornea and lens, respectively.

As shown in Fig. 1, we have derived the equation [3] $L-L2=X+ SF/f$, with $X=L-S-aT+0.05$, Eq.(1) may be rewritten in an effective eye model equation [3]

$$De = Z^2 [1336/X - D1/Z - D2] \quad (3.a)$$

$$Z=1-S/f \quad (3.b)$$

where f (in mm) is the EFL of the cornea given by $f=1336/D1$, and the nonlinear term k is about 0.003 calculated from the second-order approximation of $SF/(1336f)$. The nonlinear term may also be derived from the IOL power formula [5]. We note that in Eq. (3), X , Z , S and f are in the unit of mm; $D1$, $D2$ and De are in the unit of diopter; and the 1336 is from 1000×1.366 in our converted units.

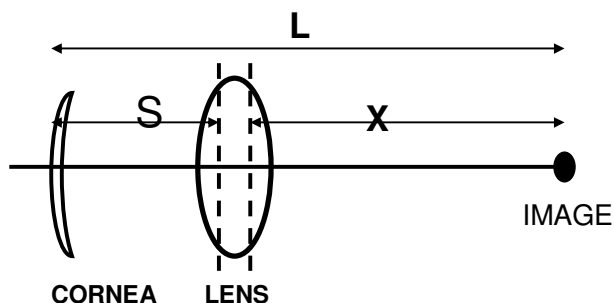


Fig. 1. An effective eye model [3] defined by the power of the cornea and lens. Also shown are the parameters of S and X which is related to the axial length by $L=S+X+aT - 0.05$ (mm)

2.2 A new standard of refractive state

The emmetropic state ("E-state", when $De=0$) can be described by a simple formula reduced from Eq.(3.a) when $1336/X = D1/Z + D2$, or as shown in Fig. 1, when the axial length at E-state (L^*) is given by $L^* = X+S+aT-0.05$, which also define the refractive states for hyperopia $De>0$ ($L<L^*$), and myopia $De<0$ ($L>L^*$). We may also easily see that at emmetropia $De=0$, or when $L=L^*$. Therefore, a new standard for E-state is governed by the relative axial length of $(L-L^*)$, rather than its absolute axial length (L). A large L^* may be due to flat cornea or lens (i.e. small $D1$ or $D2$) or deep anterior chamber depth (S), or thick lens (T). The commonly accepted concept of long axial length resulting myopia is only true under

statistical “mean”. The refractive state of a specific subject shall be defined by our new criterion as described above. For example, a subject with $L=26$ mm will have about 2.7 diopter myopia when $L^*=25$ mm, whereas it becomes about 1.4 diopter of hyperopia, when $L^*=27$ mm. The above new standard for E-state was first introduced by Lin in 2006 [3]. Using the referenced parameter set of $(f_1, f_2, S_0, T, L^*)=(31, 60, 3.3, 4.0, 24)$ mm, an ocular system deviating from this referenced-set, its emmetropic state is governed by [3] $L^*=24.0+0.36(43.1-D_1)+0.23(22.3-D_2)+0.5(S_0-3.3)+0.35(T-4.0)$.

2.3 The rate functions

To find the change of refractive error (De) due to the change of Q_j , we further define $Q_j=(r_1, r_2, R_1, R_2, t, T, S_1, S_2)$ with $j=(1$ to $8)$, respectively. The ACD (S_1) and vitreous length (S_2) are related to the axial length by $L=S_1+S_2+T$. The derivative of the refractive error (De) with respect to these ocular parameter change (Q_j) given by $M_j=dDe/dQ_j$, defines the rate function, or the change of De per unit amount change of Q_j , where the standard notation “d” for “derivative” is used in this study.

In general, under the second-order approximation including the contributions from both $n_1/(L-L_2)$ and (n_1/F) in Eq.(1), one shall rigorously calculate the derivative $dDe=M_j(dQ_j)$ based on Eq.(1). The complexity of this method is due to the nonlinear dependence of L_2 on the ocular parameters [1-3]. In this study, an alternative method is described as follows. For cornea related ocular parameters Q_j (with $j=1,2,5$), the rate function M_j may be calculated by the corneal conversion function $C_1 = (dDe/dD_1)$, such that

$$M_j = dDe/dQ_j = C_1 (dDe/dD_1). \quad (4)$$

On the other hand, the lens related parameters Q_j (with $j=3,4,6$), the rate function may be calculated by a lens conversion function $C_2 = (dDe/dD_2)$,

$$M_j = dDe/dQ_j = C_2 (dDe/dD_2). \quad (5)$$

It may be calculated, from Eq. (3.a) that $C_1=1.0$, for initial $De=0$. In other words, the corneal power change is 100% converted to the system power or refractive error change. Similarly the lens conversion function given by $C_2=Z^2$, can be derived by taking the derivative of De in Eq.(3.a).

Using Eq. (2), (3), (4) and (5) analytic formulas for the rate function for the surface curvatures and thickness of the cornea and lens are derived by $M_j=dDe/dQ_j$, with Q_j ($j= 1$ to 4 , for r_1, r_2, R_1 and R_2 , respectively), and $Q_5=t, Q_6=T$ as follows.

$$M_1 = +378/r_1^2, \quad (6.a)$$

$$M_2 = -41/r_2^2, \quad (6.b)$$

$$M_3 = +82.75 C_2/R_1^2, \quad (6.c)$$

$$M_4 = +82.75 C_2/R_2^2, \quad (6.d)$$

$$M_5 = 11.3 / (r_1 r_2), \quad (6.e)$$

$$M_6 = +4.97 C_2/(R_1 R_2). \quad (6.f)$$

where we had used the refractive indexes $n_j=(1.336, 1.336, 1.3371, 1.42)$ for the aqueous, vitreous, cornea and lens, respectively.

The rate function for S_1 and S_2 , defined by $M_7=dDe/dS_1$ and $M_8=dDe/dS_2$, were previously derived and given by [3,4]

$$M_7= 1336 (1/F^2 - 1/f^2), \quad (7.a)$$

$$M_8= - 1336/F^2, \quad (7.b)$$

where f and F (both in mm) are the corneal and system EFL given by $f=1336/D_1$ and $F=1336/D$.

Another set of useful parameter is the rate functions due to the refractive index (n_1, n_2, n_3, n_4) change which may be easily formulated by taking the derivative of Eq.(3) using an alternative technique. For example, $m_1=dDe/dn_1$ may be calculated by two steps. First step is to calculate $M_9=dD_1/dn_1 + dD_2/dn_1$, the second step is to multiply C_2 to the second term of M_1 to obtain $M_j=dDe/dQ_j$, with $Q_j(j=9,10,11,2)$ for n_j ($j=1,2,3,4$), respectively. We obtain

$$M_9= (dD_1/dn_1) + C_2 (dD_2/dn_1). \quad (8.a)$$

Similarly for n_2, n_3 and n_4 , we obtained

$$M_{10} = - 1000 C_2 / R_2, \quad (8.b)$$

$$M_{11} = - 1000 (1/r_2 - 1/r_1), \quad (8.c)$$

$$M_{12} = -1000 C_2 (1/R_1 + 1/R_2) \quad (8.d)$$

3. RESULTS AND DISCUSSION

3.1 Overall effects

By using a set of typical ocular parameters[2]: refractive indexes n_j ($j=1$ to 4) $= (1.336, 1.336, 1.3771, 1.42)$, $(r_1, r_2) = (7.8, 6.5)$ mm, $(R_1, R_2) = (10.2, 6.0)$ mm, thickness $(t, T) = (0.55, 4.0)$ mm and $S=6.0$, $S_1=3.5$ and $S_2=16.0$ mm, or an axial length of $L=3.5 + 16 + 4 = 23.5$ mm, the corneal and lens power are calculated $D_1=42$ diopter, $D_2=21.9$ diopter and total power, from Eq.(2.a), $D=D_1+0.811D_2=59.8$ diopter, The rate function M_j ($j=1$ to 6) are calculated for a 1% change of r_1, r_2, R_1, R_2, t, T : (in diopters) $M_1=+0.485$, $M_2=-0.063$, $M_3=+0.053$, $M_4=+0.091$, $M_5=+0.012$, and $M_6=-0.021$ diopters.

For 1.0 mm increase of S_1 and S_2 , the rate functions are: $M_7=+1.35$, and $M_8=-2.67$ diopter/mm. Furthermore, for each 1.0 diopter increase of corneal and lens power, the rate functions are 1.0 and 0.66 diopter, respectively, for a typical value of effective ACD, $S=6.0$ mm and corneal power of 43 diopters. We shall note that the above values of M_j depend on the choices of the ocular parameters and may vary 10% - 15% from the typical values chosen. Our calculated data are consistent with that of Ref. 2.

3.2 Effects of cornea and lens curvatures

The increase of radius of curvature of the cornea and lens (r_1, r_2, R_1, R_2) all result in hyperopic shift, except the change of the posterior surface of the lens (R_2) having a myopia shift, since it is the only concave surface and all other three surfaces (r_2, R_1, R_2) are convex. Furthermore, the effect due to anterior corneal surface change is the dominant one, where M_1 is about 8 times of M_2 and M_3 , and 5 times of M_4 , as shown by Eq. (6). This may be easily realized from Eq.(2.b) that (n_3-1) is much higher than the other terms, such as (n_3-n_1) and (n_4-n_1) . Therefore reshaping of lens surface is much less efficient than that of cornea. We will discuss more later in femtosecond laser procedure.

3.3 Effects of S_1 and S_2

The increase of S_1 results in a hyperopia shift (HS), whereas S_2 results in a myopia shift (MS), where M_8 is about two times of M_7 which has two competing terms as shown by Eq.(7.a). The rather high change rate $M_{12}=-2.67$ (D/mm) has significant impact on the onset of emmetropization and myopia which are governed by the correlation among the growth of axial length ($L=S_1+S_2+T$) and the power decrease of the cornea and lens when an eye grows [3]. The change rate M_7 having a lower value than M_8 can be analyzed as follows.

The competing between the MS (due to the increase of ACD, S_1) and the HS (due to the associate decrease of S_2 for a fixed axial length $L=S_1+S_2+T$) results in a net hyperopic-shift, because the hyperopic component is always the dominant one, since the corneal power (D_1) is always less than the total system power (D) or $F < f$ in Eq.(5.a). This new finding based on the analytic formula of Eq.(5) has not been explored before, in addition to the newly introduced conversion function.

The hyperopic shift due to the increase of S_1 is equivalent to a myopic-shift when S_1 decreases, or a forward movement of the lens. This feature is important for presbyopia accommodation which is contributed by two components: the lens curvature decrease and the lens forward movement [3,4]. The lens forward movement is also the main feature in an accommodative IOL and our formulas, Eq. (7) for M_7 and M_8 provide the amount of accommodation.

3.4 Effects of refractive index

The refractive error change (dDe) is extremely sensitive to the refractive indexes, about 0.3 to 2.5 diopters per 1% change. The increase of n_1 and n_4 result in a myopic-shift (MS), whereas the increase of n_2 and n_3 result in a hyperopic-shift (HS). These opposite behavior may be readily observed from Eq.(8). One may also find from Eq.(8.a) the reason why m_2 is larger than m_1 . This is due to the minus term CF/R_1 in Eq.(8.a) and $r_2 < R_1$, in general, which results in an MS. The HS of m_2 is given by Eq.(8.b), where R_2 is defined as the absolute value of lens posterior radius in this study. Eq.(8.c) clearly shows that m_3 has an MS due to the fact that r_2 is always smaller than r_1 , without exceptions in all human eyes. Finally, the increase of lens refractive index (n_4) always results in an MS, or becomes more power as expected from Eq.(6.d) and $n_4=1.42$ is always larger than n_1 and n_2 in Eq.(2.c).

It should be emphasized that the new feature of m_1 , based on Eq.(8.a), is not obvious due to the contribution of the second term CF/R_1 involving a rather complex mathematics to derive the formula for CF which has been ignored in most textbook formulas[6]. Another interesting situation is when both n_1

and n_2 increase the same amount of 1% (the most likely case, since the aqueous and vitreous humor are circulated, the net effect will be $dDe = -1.19 + 1.46 = +0.27$, a hyperopic-shift only about 18% of dDe due to the change of n_2 alone and shows a much less effect than that is due to the lens index change $M12=2.47$.

3.4 Clinical applications

We will present various new applications related to the formulas developed in this paper, including: laser in situ keratomileusis (LASIK) surgery, corneal cross linking (CXL) procedure, and femtosecond laser surgery. Greater details are described as follows.

3.4.1 LASIK surgery [6]

procedure called laser in situ keratomileusis (LASIK), where one diopter correction only requires an ablation depth about 8 to 11 microns of the corneal central thickness [6] or a corresponding change of r_1 about 0.16 mm based on Eq.(6.a). It is important to know that the corneal power change is 100% converted to the system power or refractive error change, as demonstrated by our cornea conversion factor C_1 . We should also note that the refractive error (De) defined on the corneal plan is the same as that of a contact lens. However, a conversion formula is needed when it is translated to a spectacle power Ds , given by $De = Ds / [1 - V Ds]$, where V is a vertex distance about 12 mm.

The central ablation depth for a 3-zone myopic correction is given by [6]

$$H'(3\text{-zone}) = RH(\text{single-zone}), \quad (9.a)$$

$$H(\text{single-zone}) = (DW^2/3)(1+C) \quad (9.b)$$

where W is the diameter of the outer ablation zone having a typical value of 6.5 to 7.5 mm; C is a nonlinear correction term given by $C = 0.19 (W/r_1)^2$, r_1 is the corneal anterior radius of curvature. For examples, for $r_1=7.8$ mm, (or a K-reading of $K=43.2$ D), $C = (11.2, 13.2, 16.5) \%$ for $W = (6.0, 6.5, 7.00)$ mm. The reduction factor $R=(0.70$ to $0.85)$ depending on the algorithms used. For example, comparing to a single zone with $W=6.5$ mm, a 3-zone depth will reduces to 71.6% (or $R = 0.716$) when an inner zone 5.5 mm and an outer zone 6.5 mm are used.

3.4.2 Age dependent lens power

It was reported that the change in the refractive index gradient of the lens cortex has a substantial factor in the contribution to the onset and progress of presbyopia [8], where an age-dependent equation for an equivalent lens index $n_{eff}=1.441 - 0.00039 \times \text{Age}$ (in year) was proposed to explain the lens paradox [9]. Lens index decreases from 1.434 to 1.416 (about 1.25% decrease) between 20 and 65 years of age to compensate the more convex shape of aged-lens, given by $R1=12.9 - 0.057 \times \text{Age}$ and $R2=6.2-0.012 \times \text{Age}$ [10], which would have caused a myopia rather than presbyopia, if n_{eff} would not be age-dependent. Above statements have been known, but only qualitatively. The formula Eq. (8.d) provides the quantitative argument that a hyperopia shift (HS) of $2.47 \times 1.25\% = 3.1$ diopter is associated to this proposed index decrease of 1.2%. The commonly accepted estimation of dDe due to the change of lens index was based on a CF value of 80% which ignored the contribution from the second principal plane, the first term of Eq.(1) in comparing to the new value of $CF=(65\%$ to $75\%)$ in this study which includes both terms.

3.4.3 Cornea cross linking [7]

Depending on the ocular location of the corneal cross linking (CXL) procedure, the new applications of CXL include examples shown as follows:

- (1) For CXL applied inside the corneal stroma, correction of low myopia is possible and may be measured by the K-value (or thickness) reduction after CXL; where 2% reduction of K-value may cause a 0.9 to 1.1 diopter myopic correction, based on the formula for $M1$, see Eq. (6.a), where $K=337/r_1$. We shall note that the refractive power change based on $M1$ calculated by the K-value change may be underestimated, because the CXL could change both the front and back surface of the cornea resulted by the thickness reduction after the CXL. A more accurate calculation should include both $M1$ and $M2$ shown by Eq. (6).
- (2) For CXL applied to the orbital scleral tissue, one may stop or reduce the abnormal axial length (L) growth rate in high myopic eyes; where each 1.0 mm increases of L may cause 2.2 to 2.8 diopter change, based on our formula for $M8$, see Eq. (7.b), assuming that the axial grow is dominated by $S2$.

(3) For CXL applied to the corneal stroma postoperatively for procedures such as conduction keratoplasty (CK), diode laser thermal keratoplasty (DTK), the postoperative regression due to unstable thermal shrinkage may be stabilized by CXL process. Eq. (6.a) for M1 may be used to estimate the amount of postoperative regression reduced by CXL.

3.4.4 Femtosecond laser surgery

One may use a femtosecond laser to ablate or remove a small portion of the lens and change its curvature (R_1), where each 1% reduction may cause a 0.05 to 0.06 diopter change, based on our formula for M3, see Eq. (6.c). This procedure is not as effective as that of corneal ablation (LASIK) given by M1 in Eq. (6.a). However, ablation of the lens has no thickness limitation like a cornea. Therefore one may ablate the lens to restore a 40% change of R_1 resulting 2.0 to 2.4 diopter accommodation. The current femtosecond laser has a very low average power and therefore lens ablation could take a much longer time than a corneal surface ablation in LASIK.

3.4.5 Scleral ablation for presbyopia treatment [8.9]

Scleral laser ablation and band expansion have been used to increase the space of the ciliary-body and zonulus such that accommodation is improved by two components [9]: the lens translation and the lens shaping which are given by, respectively, M7 and M3. For older and/or harder lens, the accommodation is mainly attributed by the lens translation (or S1 change), whereas lens shaping dominates the power change in young or soft lens. It was known that change of the rear surface of the lens is about one-third of the front surface during accommodation [10], our formulas Eq. (6.c) and (6.d) shows that the contribution from R_2 is about the same as that of R_1 , because of R_2 (6.0 mm) $< R_1$ (10.2 mm), and $M_4 = 2.9 M_3$, for the same change of curvature, $dR_1 = dR_2$.

3.4.6 Accommodative IOL (AIOL) in aphakic eye [4]

For patient after cataract, an AIOL may be implanted for vision correction to see both near and far. The accommodation formulas for M7 and M8 can be used to calculate the accommodation amplitude of the AIOL. Our calculations show the typical values of $M_7 = +1.35$, and $M_8 = -2.67$ diopter/mm. These formulas can also be used to calculate the power error of the piggy-back IOL due to mis-position. Our formulas based on the Gaussian optics are consistent with that of raytracing methods [12, 13]. Greater details may be found in Ref. [4].

In this paper, we calculate the M functions for each individual parameter independently. Our goal is to present the contribution for each component and not the combined components. The effects of combined-components or the mixed M functions are much more complex. A linear combination of our independent M functions should provide (for the first order approximate) the total effects when more than one component are changed simultaneously. In addition, a simplified model under the Gaussian optics analysis (or the paraxial ray approximation) is presented in this paper. A 2-dimensional model including the effect of ocular aberrations may be more realistic. However, it will need numerical calculations and can not provide analytic formulas as presented in this paper.

This paper also assumes that the crystalline lens is a uniform refractive index medium. If a gradient refractive index parameter were included, our formulas will need revision, particularly the effective anterior chamber depth, $S = S_1 + P_{11} + 0.05$, where P_{11} needs to be redefined as a mean value over the gradient of the lens refractive index. However, our basic analytic formulas will remain the same under the mean value of S (or P_{11}).

4. CONCLUSION

Using Gaussian optics, we have derived analytic formulas for the change of refractive power due to various ocular parameter changes. These formulas provide the amount of refractive error corrections in various applications including laser in situ keratomileusis (LASIK) surgery, corneal cross linking (CXL) procedure, femtosecond laser surgery and scleral ablation for accommodation.

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