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Clinical Applications of Human Ocular Optics in Vision Corrections and Lens Accommodation

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ABSTRACT

Aim: To analyze the clinical factors influencing the human vision corrections and lens accommodation via the changing of ocular components of human eye in various applications.

Methods: An effective eye model is introduced by the ocular components of human eye including refractive indexes, anterior surface radius of the cornea (r) and lens (R), the anterior chamber depth(S1) and the vitreous length (S2). Gaussian optics is used to calculate the change rate of refractive error per unit amount of ocular components of a human eye (the rate function M).

Results: For typical corneal and lens power of 42 and 21.9 diopters, the rate function Mj (j=1 to 4) are calculated for a 1% change of r and R: M1=+0.485, M2=-0.063, and 1.0 mm change of S1 and S2: M3=+1.35, M4=-2.7 diopters/mm. These rate functions are used to analyze the clinical outcomes in various applications including laser in situ keratomileusis (LASIK) surgery, corneal cross linking (CXL) procedure, femtosecond laser surgery and scleral ablation for accommodation.

Conclusion: Using Gaussian optics, analytic formulas are presented for the change of refractive power due to various ocular parameter changes. These formulas provide useful clinical guidance in refractive surgery and other related procedures.

Keywords: Gaussian optics, intraocular lens power, accommodative lens, refractive errors, vision correction.

INTRODUCTION

The IBM patent (1983) of UV laser for organic tissue ablation was developed into clinical application for the first human trial of (photorefractive keratoplasty (PRK) in 1987 and followed by US FDA approval in 1995. The flying-spot scanning technology invented by Lin (US 1991 patent) leading to the customized LASIK which was US FDA approved in 2002. The combined technologies of scanning laser, eye tracking, topography and wavefront sensor advance the corneal reshaping (the refractive surgery) one step further from the conventional ablation of spherical surface to the customized ablation of aspherical surface. Therefore, the theory (or mathematics) behind LASIK is also expanded from the simple paraxial formula to the high-order nonlinear formulas involving the change of the corneal asphericity and the LASIK-induced surface aberrations. Most of the existing LASIK monograms are based on spherical corneal surface. The customized nomograms require aspherical surface in order to minimize the optical aberrations [1-4].

Besides the 193 nm excimer laser, various laser systems/procedures were developed during 1995-2000, including [1]: laser thermal keratoplasty (LTK, using Ho: YAG), diode laser TK (using diode laser at 1540 nm), radio frequency and conducting keratoplasty (RF and CK) designed for hyperopia corrections; UV solid state lasers (213 nm for PRK), YAG pico-second-PRK, Mini-Excimer for PRK etc. Technologies developed in the 2000's include: eye-tracking device (Lai, Nvatek), microkeratome, Elevation map, topography-guided LASIK, wavefront for customized LASIK (Tracey), presbyopia treatment using SEB (Schachar) and laser scleral-ablation for presbyopia (Lin); accommodative IOL. More recently, femto-second lasers are developed for flat cutting, stroma ablation and cataract. UV-light and riboflavin activated corneal cross linking (CXL) has been developed for clinical use for various corneal deceases such as corneal keratoconus, corneal keratitis, corneal ectasia, corneal ulcers, and thin corneas prior to LASIK vision corrections.

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Combined technology of CXL-PRK, CXL-intra stroma-femto-laser pocket, CXL-phakic-IOL, CXL-IC-ring. Summary of various ophthalmic lasers is shown in **Table 1**. Summary of lasers for vision corrections are shown in **Figure 1 and 2**, cataloged by the treatment arears of corneal surface (6-8 mm), scleral (8-13 mm), intrastroma, lens and retina.

Table 1. Summary of Ophthalmic Lasers and Applications [1]

Laser (wavelength, pulse width)	**Applications**
(1) Excimer ArF (193 nm, 5-20 n.s.)………….	PRK, LASIK, LASEK
(2) Excimer XeCl (308 nm, 200 n.s.)…............	Glaucoma
(3) Argon Ion (488/514 nm, CW)……………..	Coagulation, glaucoma
(4) Diode laser (810 nm, cw)…….	TTT (CNV, AMD glaucoma/TCPC
(1.4 to 2.1 micron, cw)……….	DTK (hyperopia),
(5) Nd:YAG (1064 nm, pulsed)………………	posterior capsulotomy, phaco
(6) Green Nd:YAG (532 nm, 3-10 n.s.)………	PDT (for CNV or AMD)
Yellow Nd:YAG (580 nm, cw)	combined with photosensitizers
Blue Nd:YAG (460 nm, cw)	
Diode lasers (680, 755, 810 nm)	
(7) UV:YAG (213-266 nm, 3-20 n.s.)………..	LASIK, LAPR (presbyopia)
(8) Ho:YAG (2.1 micron, 200 us)…………….	LTK (hyperopia)
(9) Er:YAG and YSGG …………………….	LAPR (presbyopia), phaco-
(2.8-2.94 micron, 200 u.s)………….	emulsification, blepharoplasty
(10) CO_2 (10.6 micron, ultra-pulsed)………….	Blepharoplasty
(11) Femto-laser (1047 nm, femtosec)	femto-flat, femto-pocket (SMILE),
	femto-cataracts
(12) UV diode laser or LED (365 nm)	corneal cross linking (CXL)

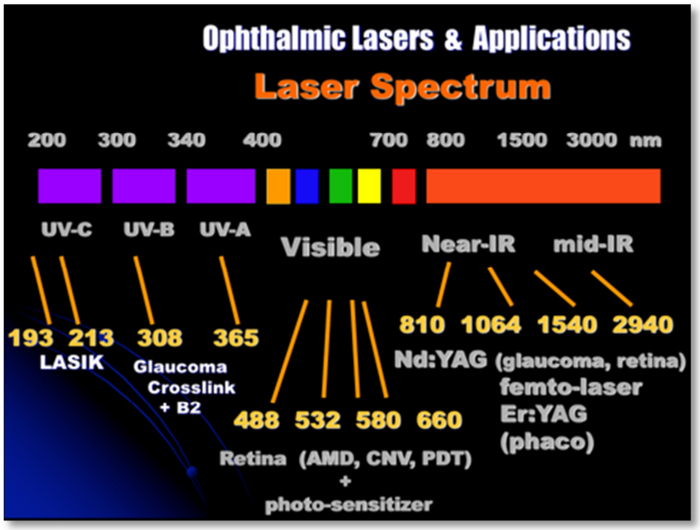


Figure 1. Laser spectra from UV to IR for various ophthalmic applications [1].

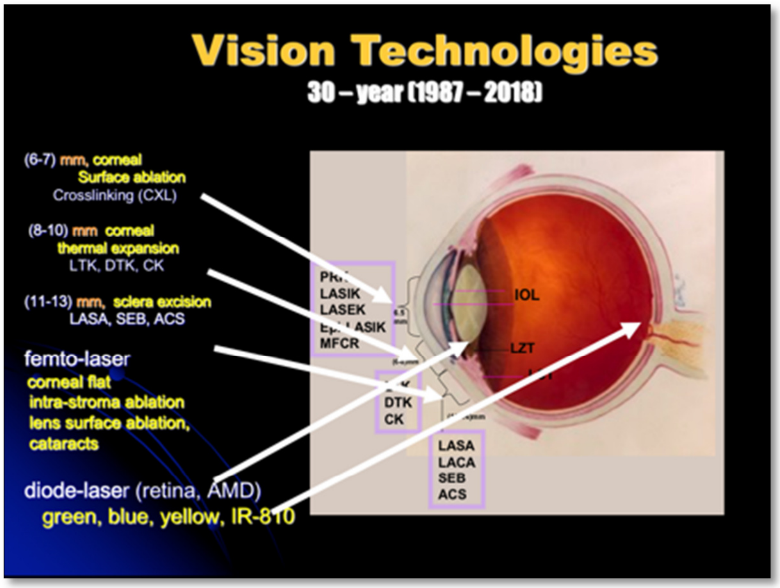


Figure 2. Various laser technologies acting on the, crystal lens, and retina for PRK, LASIK, LAPR, ACS, femto-SMILE, femto-cataracts and AMD.

MATERIALS AND METHODS

We will present various applications and the related theoretical background (or mathematical formulas) including: laser in situ keratomileusis (LASIK) surgery, femtosecond laser surgery, corneal cross linking (CXL) and accommodative IOL.

Human ocular optics

As shown in **Figure 3**, an effective eye model was developed for comprehensive description of human ocular optics based on Gaussian paraxial approximation [4]. The refractive error (De) is given by

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

where n1 is the refractive index of the aqueous humor, L is the axial length, L2 is position of the system second principal plane and F is the system effective focal length (EFL). The system total power is given by D=1000n1/F (D in diopter, F in mm) which is determined by the corneal (D1) and lens power (D2) as follows: $D = D1 + D2 - S(D1D2)/(1000n1)$, with corneal power $D1 = 1000\ [(n3-1)/r1 - (n3-n1)/r2] + bt$; and lens power given by $D2 = 1000\ [(n4-n1)/R1 + (n4-n2)/R2] - aT$;

where nj (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, using L-L2=X+ SF/f, with X=L-S-aT+0.05, and aT and 0.05 are the correction factors for the lens and cornea thickness, Eq.(1) may be rewritten in an effective eye model equation [4]

$$De = Z^2\ [1336/X - D1/Z - D2] \qquad (2)$$

where Z=1-S/f , with 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 1000x1.366 in our converted units.

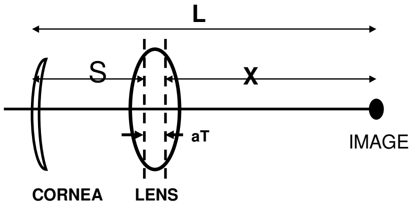


Figure 3. An effective eye model [6] defined by the power of the cornea and lens. Also shown are the parameters of S and X which is related to the axial length by L=S+X+aT - 0.05 (mm) [4].

The Rate functions

To find the change of refractive error (De) due to the change of ocular components, the anterior chamber depth (S1) and vitreous length (S2), related to the axial length by L=S1+S2+T. The derivative of the refractive error (De) with respect to these ocular parameter change (Qj) given by Mj=dDe/dQj, defines the rate function, or the change of De per unit amount change of Qj. The rate function for Qj is anterior curvature of cornea (r), lens (R), S1 and S2, defined by M1=dDe/dQj were previously derived and given by [4].

$M1 = +378/r^2$ (3.a)

$M2= +82.75\ (Z/R)^2$, (3.b)

$M3= 1336\ (1/F^2 - 1/f^2)$ (3.c)

$M4= -\ 1336/F^2$ (3.d)

where f and F (both in mm) are the corneal and system EFL given by f=1336/D1 and F=1336/D; and Z=1-S/f. Eq. (3.c) is for the rate function for the lens anterior curvature (R) change in femtosecond procedure to be discussed later. For typical values of r=7.8 mm, R=10.2 mm, S=6.0, S1=3.5 and S2=16.0 mm, axial length of L=3.5 + 16 + 4 = 23.5 mm, the corneal and lens power are calculated D1=42 diopter, D2=21.9 diopter and total power, from Eq.(2.a), D=D1+0.811D2=59.8 diopter, The typical rate functions are calculated for a 1% change of r,R, S1, S2 (in diopters): M1=+0.49, M2=+0.053, M3=+1.35, and M4=-2.67 diopter/mm. Clinical applications of above rate functions are discussed as follows.

RESULTS AND DISCUSSIONS

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

LASIK procedure

A 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 or a corresponding change of r1 about 0.16 mm. In LASIK procedure, the refractive power change is defined by the difference of the preoperative (R) and postoperative (R') front surface radius of the cornea, given by D = 377(1/R – 1/R'), where D in diopter (or 1/m) and R and R' in mm. Therefore, myopia (D<0), R'>R and hyperipia (D>0), R'<R. For examples, for a preoperative R=7.7 mm, D=(-1,-5,-10,+1, +5, +10), for R'=(8.0, 8.6, 9.7,7.4,7.0, 6.4) mm.

The central ablation depth for a 3-zone myopic correction is given by [3,5]

H'(3-zone) = RxH(single-zone) (4.a)

$H(\text{single-zone}) = (DW^2/3)(1+C)$ (4.b)

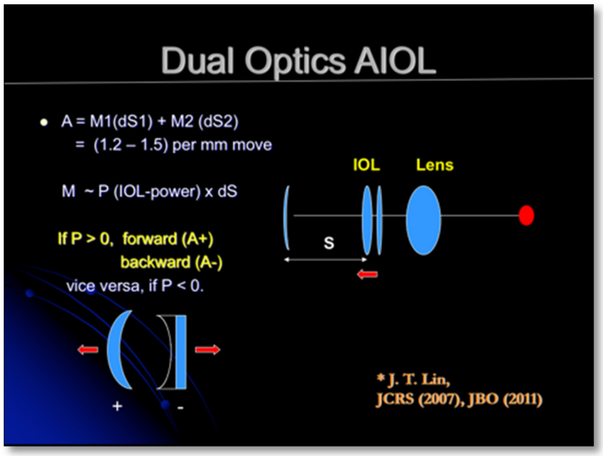
Where, W is the diameter of the outer ablation zone having a typical value of 6.5 to 7.5 mm; C is a nonlinear correction term given by $C= 0.19\ (W/r1)^2$, r is the corneal anterior radius of curvature. For examples, for r1=7.8 mm, (or a K-reading of K=337.R1=43.2 D), C = (11.2, 13.2,16.5) % for W =(6.0, 6.5, 7.0) 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. Furthermore, in a LASIK system, the input pre-operative parameter of the treated eye must include the K values which affect the laser ablation depth via the nonlinear term of Eq. (4.b). Modern customized LASK parameters includes: D, K, and Q-value to correct the asphericity and the LASIK-induced surface aberrations [3,5].

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 [6], where an age-dependent equation for an equivalent lens index neff=1.441 – 0.00039 x Age (in year) was proposed to explain the lens paradox [7]. 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 – 0.057xAge and R2=6.2-0.012 x Age [7], which would have caused a myopia rather than presbyopia, if neff would not be age-dependent. Above statements have been known, but only qualitatively. The formula shows that a hyperopia shift of 2.47 x 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 conversion factor ($CF=Z^2$) of 80% which ignored the contribution from the second principal plane, in comparing to our new value of CF=(65% to 75%).

Accommodative IOL (AIOL)

For patient after cataract, an AIOL in an aphakic eye may be implanted for vision correction to see both near and far. The accommodation formulas for M1 and M2 can be used to calculate the accommodation amplitude of the AIOL. Our calculations show the typical values of M3=+1.35, and M4=-2.67 diopter/mm. These formulas can also be used to calculate the power error of the piggy-back IOL due to mis-position [8]. **Figure 4** shows the dual optic for AIOL showing 2-component model for lens accommodation.



Dual Optics AIOL

- A = M1(dS1) + M2 (dS2)
  = (1.2 – 1.5) per mm move

M ~ P (IOL-power) x dS

If P > 0, forward (A+)
backward (A-)
vice versa, if P < 0.

*J. T. Lin,
JCRS (2007), JBO (2011)

Figure 4. The dual optic for AIOL showing 2-component model for lens accommodation.

Femtosecond laser surgery

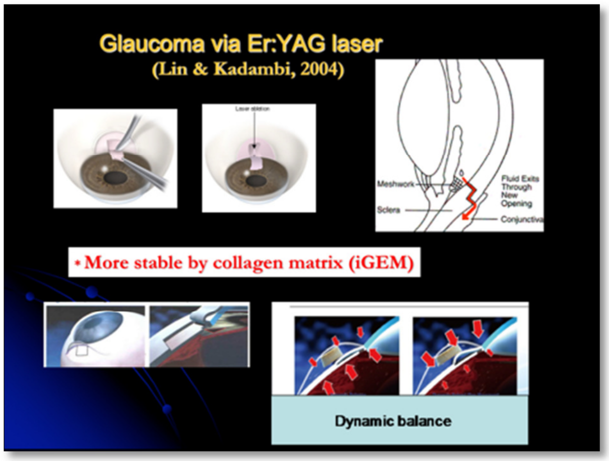
One may use a femtosecond laser (so called SMILE) to ablate or remove a small portion of the lens and change its curvature (R), where each 1% reduction may cause a 0.05 to 0.06 diopter change, based on our formula for M2, see Eq. (3.b). This procedure is not as effective as that of corneal ablation (LASIK) given by M1 in Eq. (3.a). Therefore, one may ablate the lens to restore a 40% change of R 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.

Scleral ablation for presbyopia treatment

Scleral laser ablation (using Er: YAG laser at 2.94 um) and band expansion have been used to increase the space of the ciliary-body and zonus such that accommodation is improved by two components [9,10]: the lens translation and the lens shaping which are given by, respectively, M3 and M2. 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 [9,10].

Scleral ablation for glaucoma treatment

As shown by **Figure 5** besides presbyopia treatment, Er: YAG laser can also be used for glaucoma treatment, followed by a collagen matrix refilling to stable the outcomes.



Glaucoma via Er:YAG laser
(Lin & Kadambi, 2004)

- More stable by collagen matrix (iGEM)

Dynamic balance

Figure 5. Schematic of glaucoma treatment via an Er: YAG laser ablation and collagen matrix to stable the outcomes.

Cornea cross linking

Depending on the ocular location of the corneal cross linking (CXL) procedure, the new applications of CXL include examples shown as follows [11,13]:

(1) For CXL applied inside the corneal stroma, correction of low myopia is possible and may be measured by the K-value deduction 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. (3.a), with K=337/r.

(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 M4, see Eq. (3.d), 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. (3.a) for M1 may be used to estimate the amount of postoperative regression reduced by CXL.

(3) Combined CXL with OK-lens or RPG-lens to stabilize regress. The reshaping effect of corneal anterial surface may be estimated by M1 of Eq. (3.a).

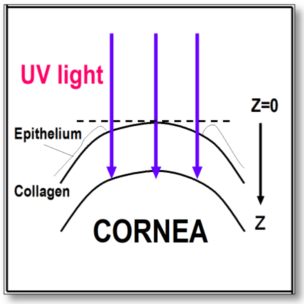


Figure 6. Shows the schematics of corneal collagen crosslinking showing a UV (365 nm) light activated

riboflavin solution in the stroma causing stiffness increase of the stroma.

CONCLUSION

Using Gaussian optics, we have presented analytic formulas for the change of refractive power due to various ocular parameter changes. These formulas provide useful clinical guidance in various applications including LASIK surgery, corneal cross linking (CXL) procedure, femtosecond laser surgery and scleral ablation for accommodation. Accuracy of our formulas for human eyes would depend on individual ocular parameters, which were taken as their averaged values in our calculations.

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