Analysis of Accommodation Gain of Presbyopia Eye after Laser Ablation (or Shrinkage) of Sclera via Lens Reshaping and Anterior Shift

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ABSTRACT

Purpose: To derive and provide analytic formulas for accommodative gain of presbyopia eyes via sclera ablation and/or thermal shrinkage such that lens is reshaped an/or its position is shifted. New mechanisms are also proposed.

Study Design: To increased accommodation of presbyopia.

Place and Duration of Study: New Taipei City, Taiwan, between June, 2021 and July, 2021.

Methodology: Accommodation gain is calculated by a 4-component theory, in which the rate functions are derived by an effective eye model for the change of anterior curvature of the lens and its anterior shift. The measured data of accommodative response of the lens versus the lens curvature change and anterior shift are analyzed. The measured net change of the posterior vitreal zonules (PVZ) length and the space between the ciliary body and lens (CLS) during the accommodation are also analyzed.

Results: The accommodative gain (AG) is mainly due the change of lens anterior curvature and its anterior shift. The AG per diopter change of the reshaped lens is 0.62 to 0.68 by our formulas, comparing to the measured average value M'=0.69. The efficacy of LASA (or AG) is proportional to the amount of scleral tissue removed (or shrinkaged), such that more space is produced for the change of PVZ and CLS from a UCS to AS for accommodation.

Conclusion: The AG is proportional to the amount of scleral tissue removed (or shrinkaged), such that more space is produced for the change of PVZ and CLS from a UCS to AS for accommodation.

Keywords: Presbyopia; accommodation; scleral ablation; ciliary body; lens reshaping; lens anterior shift.

1. INTRODUCTION

Presbyopia affects over 1.3 billion populations worldwide, for age over 50. The principles of presbyopia were given by the classical hypothesis of von Helmholtz [4] and Schachar [5-7], and the modern theory of Lin [8-12]. Non-traditional methods [5-12] for presbyopia correction including: Schachar using scleral band expansion [5-7] and scleral tissue ablation via IR laser of Er: YAG (at 2.94 um) and UV laser (at 266 nm) [8-10]. Prior art of US patent, Lin and Martin [13], proposed a non-invasive method using a gonio lens guided infrared laser to heat the zonules fiber of the eye for the treatment of presbyopia.

The present author also proposed various methods for presbyopia corrections combining laser surgery and pharmacologic means [14]. Thermal shrinkage of scleral stroma was also disclosed by US Pub No. US20200000634 using long wavelength at about 5.8 to 6.5 microns, in which means of thermal sink to avoid the overheating of the corneal surface of conjunctiva was also proposed. However, these prior arts are not patentable due to their lack of merits. By the same reasons, there are few prior US Publications having proposed various methods for presbyopia treatment, but not yet patented. Most of the prior arts of non-patented-Publications are due to their similarity to the methods patented by the present author [13].

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Technology for presbyopia corrections include [5,8-13]; SEB (scleral expansion band), SRI (scleral radial incision by knife), SEP (silicon expansion plugs), BIC (band implanted in ciliary body), LPR (laser presbyopia reversal using scleral ablation), CK (conductive keratoplasty), DTK (diode laser thermal keratoplasty), LASIK (presbyopia LASIK using monovision), AIOL (accommodative IOL). The accommodative theory postulated by Helmholtz (in 1855) [4] remains the most widely supported and cited despite alternative theories proposed subsequently by Schachar et al [5-7]. As traditionally accepted Helmholtz hypothesis, presbyopia is due to progressive weakening or atrophy of the ciliary muscles [4]. Consequently, the ciliary muscle is left with no space to contract. Thus, with a view to give the muscle “more room” for contraction. Helmholtz [4] proposed that (as shown in Fig.1) the ciliary muscles contract which relaxes the zonules causing the lens capsule to become relax. The jelly like lens material hence bulges in the center. There is a decrease in the equatorial diameter in the process. Schachar et al [5], on the other hand, postulates that when the ciliary muscles contract the “equatorial” zonules tighten while the non-equatorial zonules relax. Comments on Schachar’s theory, the concept of scleral expansion is under hot debate. Many studies have actually discounted Schachar hypothesis.

In the present article, we will first review the prior arts and the classical accommodation theory of Helmholtz [4]. An effective eye model is presented to derive the accommodative gain (AG), which is given by a 4-component theory. The measured data of accommodative response of the lens versus the lens curvature change and anterior shift are analyzed. Finally, the measured net change of the posterior vitreal zonules (PVZ) length and the space between the ciliary body and lens (CLS) during the accommodation are also analyzed.

![Fig. 1. Schematic eye structure for accommodation based on Helmholtz theory [4]: left-half is for unaccommodated-state, and right-half is for accommodated-state, showing the relax of the zonular fibers.](image)

2. MATERIALS AND METHODS

2.1 The ageing effects of human eyes

Many theories have been proposed for the age-related loss of accommodation including: (a) lens-based theories; (b) geometric theories; (c) lenticular theories; and (d) multi-factor theory [15,16]. The factors, which may contribute to changes in overall refractive power, include the corneal shape and thickness, lens shape and thickness, anterior and vitreous chamber depth and globe axial length. Refractive index gradient change of the lens cortex, lens thickness change, and anterior shift of the zonular attachments were suggested as the key factors contributing to the progression of presbyopia.
Cross-sectional studies of age-related changes in resting refraction show a drift towards hyperopia from about age 30 to 65 years and then a drift towards myopia after age 65 year attributed to growth and the forward movement of the lens [16]. It should be noted that the “lens paradox” showing ‘myopic-shift’ with ageing (due to lens curvature changes) may be counter-balanced by all those factors which may cause a hyper-shift including the decreases of lens equivalent index and globe axial length with age. We shall also note that the increase of lens power due to radii decrease is a weaker age-dependence that the of the equivalent refractive index change, therefore the “net effects” cause a “hyper-shift” by ageing [16,17].

2.2 The Effective Eye Model
Using paraxial ray approximation, (or Gaussian optics theory) the total power of an eye (De) is related to the corneal power (D') and lens power (D) as follows [18]

\[ D_e = D' + D - S(DD')/(1000n1), \]  

(1)

where,

\[ D' = 1000 [(n3-1)/r - (n3-n1)/r'] + bt, \]  

(2.a)

\[ D = 1000 [(n4-n1)/R - (n4-n2)/R'] - aT, \]  

(2.b)

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 (r, r') and (R, R'), respectively, noting that R'<0 for a concave surface. Finally, S is the effective anterior chamber depth. b=11.3/(r1r2), a=[(n4-n1)^2/n4]=(4.97/(RR')), t and T are the thickness of the cornea and lens, respectively. For T=3.7, R=11.6, R'=6.3, we obtain aT=0.25. Lens power D=84(1/R - 1/R') - aT=20.3D.

As shown in Fig. 2 for an effective eye model, Eq. (1) becomes [18,19]

\[ De = Z^2 \left[ \frac{1336}{X - D'/Z - D} \right] \]  

(3.a)

\[ Z=1-S/f= 1-S(D'/1336) \]  

(3.b)

where f (in mm) is the EFL of the cornea given by f=1336/D'.

Fig. 2. Schematic of an effective eye model, where the axial length is given by L=S+X+aT - 0.05 (mm) [18,19].

2.3 The Rate Functions
Taking the derivative of the eye power (De) with respect to the change of ocular parameter (Qj), we obtain the rate function defined by Mj=dDe/dQj, with Qj (j= 1 to 6), for (r, r', R, R', S1, S2) as follows [18,19]

\[ M1 = +378/r^2, \]  

(4.a)
M2 = -41/r^2, \hspace{1cm} (4.b)
M3 = +82.75 \frac{C_F}{R^2}, \hspace{1cm} (4.c)
M4 = +82.75 \frac{C_F}{R'^2}, \hspace{1cm} (4.d)
M5 = 1336 \left(1/f^2 - 1/f'^2 \right), \hspace{1cm} (4.e)
M6 = -1336/F^2, \hspace{1cm} (4.f)

where \( C_F \) is a conversion function, from lens power translated to eye power, given by \( C_F = (dD_0/dD) = Z^2 \); with \( f=1336/D' \) and \( F=1336/D \).

2.4 Accommodative eye model

As shown in Fig. 3, a 4-component theory for the accommodative gain (AG) is proposed (21,22)

\[
AG = m \ dR + m' \ dR' + M \ dS_1 + M' \ dS_2 \hspace{1cm} (5)
\]

where the AG is attributed by 4 components: front (dR) and anterior (dR') lens curvature change, anterior chamber depth (ACD) change, dS1 and vitreous length change (dS2). The rate functions are defined in Eq. (4), with renamed notations: \( m=M_5, m'=M_6, M'=M_3 \) and \( M'=M_4 \).

2.5 The accommodative lens reshaping

It was known that accommodation may be improved by: (i) thermal shrinkage (with temperature range of 50°C to 70°C) of the scleral stroma such that the space between the ciliary body and lens (CLS), or ciliary apex ring diameter increases; or (ii) softening of the scleral stroma (with temperature range of 70°C to 90°C), and (iii) laser ablation (tissue removal) of scleral stoma, such that the net change of the posterior vitreal zonules (PVZ) length and CLS increase during the accommodation.

As shown in Fig. 4, a lens reshaping model for AG due to decrease of CLS (with relaxed zonular fiber), and decrease of PVZ, where the left figure shows relaxed zonular fiber with CLS space from A to B, resulting the increase of lens lens anterior radius of curvature (dc) such that the focused image is myopic-shifted to see near (for dR>0) at the accommodative-mode, or a positive AG. Defining the CLS decrease (dc) given by the distance AB, and dR given by the distance DE, and under a balance condition of \( AD=BE \), we obtain dR is related to dc by the solution of (using a simple geometry shown in Fig.4)

\[
dR^2 + 2(dR)(DC) - (dc)^2 - 2(dc)(BC) = 0 \hspace{1cm} (6)
\]

Because \( dc<<BC \) and \( dR<<DC \), Eq. (6) reduces to \( dR=(BC/DC)(dc) \). We note that combining Eq. (5) and (6) allows us to to estimate the AG and dR as a function of dc, to be shown later.

Fig. 3 Schematics of an accommodating eye showing the anterior shift of the lens (with decreasing distance, S), and its surface curvatures, R and R' (becoming more curved).
Fig. 4 The lens reshaping model for AG due to increase of CLS (dc) with relaxed zonular fiber, and decrease of PVZ, where the left figure shows CLS decrease (from A to B) resulting the increase of lens anterior radius of curvature (dR, from D to E).

3. RESULTS AND DISCUSSIONS

3.1 The formulas for accommodative gain (AG)

For typical ocular parameters: \((r', r_2) = (7.8, 6.5) \text{ mm}, (R, R') = (10.2, 6.0) \text{ mm}, (t, T) = (0.55, 4.0) \text{ mm}\); and \(S=6.0, S_1=3.5\) and \(S_2=16.0 \text{ mm}\). we obtain the rate function \(M_1=+6.2, M_2=-0.97, M_3=0.53, M_4=1.48, M_5=+1.35, \) and \(M_6=-2.67 \text{ dioptr/mm}\). The conversion function which translates the change of the lens power to the whole eye power, having a typical value of \(C_F=0.62\) to 0.68.

One may also calculate the reported pseudo-accommodation caused by a myopic shift -2.6 diopter for an axial length increase 0.89 mm (with steady-state axial length of \(L=22.94 \text{ mm}\)). However, Uozato (Uozato, ARVO Meeting, 2003, Abstract) measured a very small axial length elongation (mean of 0.06mm) in true accommodation. It was known that change of the rear surface of the lens is about one-third of the front surface during accommodation, our formula shows that the AG contribution from posterior radius change (\(dR'\)) is about the same as that of anterior change (\(dR\)), because of \(R'\) (6.0 mm) < \(R\) (10.2 mm), and rate function \(m'=2.9 \text{ m}\). We note that for older (or hard lens), the AG is mainly attributed by the lens translation (or \(dS_1\) and \(dS_2\)), whereas lens shaping dominates the power change in young or soft lens.

Given typical rate functions of \(m=M5=0.53, m'=M6=1.48, M=M3=1.35\) and \(M'=M4=-2.67 \text{ (D/mm)}\), we may calculate the AG given by Eq. (5). However, the change of \(dR, dR', dS_1, dS_2\) are correlated by: 
\[
dR \text{ also induces } dS_1=dR, \quad \text{and } dR' \text{ also induces } dS_2=dR'.
\]
Therefore, Eq. (5) becomes
\[
AG = (m + M) \ dR \quad (7)
\]
due to lens anterior curvature change (\(dR\)) and the associated anterior shift (\(dS_1=dR\)). For typical value of \(m=0.53, \) and \(M=1.35\), we obtain \(AG=1.88 \text{ dR}\), that is the rate function of AG due to lens anterior curvature increase (or myopic shift) defined by \(R'_A=dR/d(AG)=11/1.88=-0.53 \text{ (mm/D)}\), which is comparable to the measured data of 0.6 by Martinez-Enriquez et al [23].

Similarly, the change of \(dR'\) also induces \(dS_2=dR'\), therefore, the AG of Eq. (5) becomes
\[
AG' = (m' + M') \ dR' \quad (8)
\]
For typical value of \(m'=1.48, \) and \(M'=-2.67 \text{ (D/mm)}\), \(AG'=4.15dR'\), we obtain another rate function \(AG'=dR'/d(AG')=1/4.15=-0.24\), which is comparable to the measured data of 0.22 by Martinez-Enriquez et al [23]. we not that AG is more sensitive to \(dR'\) and \(dR\), because typical value of \(R'=6.0 \text{ mm}\), much smaller than \(R=10.2 \text{ mm}\). These theoretical predicted values (for \(dR\) and \(dR'\) are very close to (within 10%) the measured data of Martinez-Enriquez et al [23]. However, our theory did not calculate the rate functions due to ACD change or lens thickness change (\(dT\)), which need much complex calculations, while the actual measured data are not well defined. Fig. 5 shows the measured average rate functions (or slopes) (shown in bars and dashed curves), and theoretical curves (in solid red curves)
Fig. 5 shows the measured data of Martinez-Enriquez et al [23] for the rate function $R_C$ defined as the AG per diopter change of the reshaped lens, or $R_C = dD_e/dD = C_F = 0.62$ to 0.68, comparing to the measured average value $M' = 0.69$.

Fig. 5 Measured data of accommodative response of the lens vs. various ocular parameters of Martinez-Enriquez et al [23], shown in bars and dashed curves; and theoretical curves (in solid red curves); for the change of lens curvatures (dR and dR'), top figures; and anterior shift, d(ACD) and corneal thickness change, d(LT), low figures.

Fig. 6 The measured data of Martinez-Enriquez et al [23] for the rate function (or slope) shown by bars and dashed curve having an average value $M' = 0.69$, comparing to the theoretical curves (solid curves) with $M' = 0.62$ to 0.68.

3.2 Analysis of measured accommodative gain

Combining Eq. (5) and (6) allows us to calculate the AG (or dR) for a given ((measured) value of CLS increase (dc) as follows. It was reported by Herek and Herek [24] (US Pub. No. 2020/0000634) that in non-presbyopic eyes, the length of PVZ changes from 4.6 mm in the un-accommodative state...
(UAS) to 3.6 mm in the accommodative state (AS) for a net change of 1.0 mm. In comparison, PVZ mobility is substantially reduced in presbyopic eyes: the PVZ length changes from 4.6 mm in the UAS to 4.45 mm in AS, for a net change of only 0.15 mm. Furthermore, the CLS is significantly smaller in presbyopic eyes compared to non-presbyopic eyes: with measured values of 0.68 mm and 0.35 mm (in UAS) and 0.68 mm and 0.2 mm (in AS), respectively. They also reported that the mid-stroma of the sclera can be heated to approximately 60°C to increase scleral elasticity and shrink the mid-stroma within a range of 100 um to 250 um of shrinkage, and thereby increase the CLS within a rage from 200 to 500 um. The inward mobility of the ciliary body can be enhanced post-treatment by approximately 250 um.

Based on above reported data, and the reduced formula of Eq (6), \( dR = (BC/DC)(dc) \). For example, for \( dc = 0.3 \text{ mm} \), we obtain \( dR = 0.9 \text{ mm} \), if \( BC/DC = 3 \). These data may be related to our formula, Eq. (7), \( AG = (m+M)dR = 1.88 \times 0.9 = 1.69 \text{ D} \). Another example is that McDonald et al reported an eye at age 53 administered by pilocarpine induced an accommodation of 4.25 diopter after scleral buckling. Lens thickness increase (\( dt \)) 0.18 mm and anterior shift (\( dS \)) 0.57 mm were measured associated with the total accommodation \( AG = M(dS) + m(dR) = A_1 + A_2 \), calculated by our theory to be \( A_1 = 0.53 \text{ D} \) and \( A_2 = 3.78 \text{ D} \), where a net anterior shift \( dS = -0.57 + 0.18 = -0.39 \text{ mm} \) and change rate \( m = 1.36 \text{ (D/mm)} \) are used.

### 3.4. Laser sclera ablation

Lin and Mallo [25] reported the laser sclera ablation (LASA) procedures for presbyopia patients (age 42-60, mean 53.2) to cause a mean true accommodation of 1.96 diopter, without myopic-shift induced pseudo-accommodation. This was justified by no change of the far vision or corneal topography in treated eyes or comparing the pre-operative and post-operative keratometer (K) readings. Lin propose a two-component theory [21]. The efficacy of LASA (or AG) is proposed to be proportional to the amount of scleral tissue (AST) removed (or shrinkaged), such that more space is produced for the change of PVZ and CLS from a UCS to AS for accommodation. As reported data of Herek and Kerek [24] that a net change of 1.0 mm of the PVZ length (from 4.6 mm in the UAS to 3.6 mm in the AS), for a non-presbyopia eye versus only 0.15 mm for a presbyopia eye, which also has a small UAS space of CLS about 0.35 mm (vs. 0.68 mm of non-presbyopia). Therefore, LASA produces increased PVZ and CLS at UAS, such that larger AG is achieved when the the zonular fibers are relaxed from UAS to its AS. We have derived the formula, Eq. (6), relating \( dR \) (or AG) and \( dc \) of CLS. However, the actual value of \( dR \) (and AG) requires accurate data for the distance of BC and CD in Fig. 3; and the relation of amount of sclera tissue (AST) removed (or shrinkaged) and \( dc \) (or \( dR \)). Based on the reported clinical outcomes of Lin et al [25,26], Xu et al [27], Kaiti et al [28] and Hispley et al [29,30], we found out that the efficacy of LASA (or AG) is mainly governed by AST, and insensitive to the ablation patterns (either lines or dots).

### 4. CONCLUSION

The principles of accommodation and the key factors influencing the outcomes are discussed, where the amount of accommodation gain (AG) after the laser scleral ablation is predicted by analytic formulas based on a 4-component theory that AG is mainly due the lens anterior curvature change and its anterior shift. The AG per diopter change of the reshaped lens is 0.62 to 0.68 by our formulas, comparing to the measured average value \( M' = 0.69 \). The measured data of OCT-based lens shape change during accommodation are analyzed by analytic formulas. Net change of 1.0 mm of the PVZ length (from 4.6 mm in the UAS to 3.6 mm in the AS), for a non-presbyopia eye versus only 0.15 mm for a presbyopia eye, which also has a small UAS space of CLS about 0.35 mm (vs. 0.68 mm of non-presbyopia). The efficacy of LASA (or AG) is proportional to the amount of scleral tissue removed (or shrinkaged), such that more space is produced for the change of PVZ and CLS from a UCS to AS for accommodation.
CONSENT
It is not applicable.

ETHICAL APPROVAL
It is not applicable.

COMPETING INTERESTS
The author is the CEO of New Vision Inc. and has financial interest.

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