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Dynamic accommodation in rhesus monkeys

Abhiram S. Vilupuru, Adrian Glasser *

College of Optometry, University of Houston, 4901 Calhoun Road, Houston, TX 77004, USA

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Abstract

The dynamics of Edinger–Westphal (EW) stimulated accommodation were studied in two young rhesus monkeys to understand the relationships between accommodative amplitude and rates of accommodation and disaccommodation. Accommodative responses were recorded with infrared photorefraction at five different amplitudes spanning the full EW stimulated accommodative range available to each eye. Combined exponential and polynomial functions were fit to the accommodation and disaccommodation responses. Derivatives of these functions provided the maximum rates of accommodation and disaccommodation as well as time constants for each amplitude. Maximum rates of EW stimulated accommodation and disaccommodation were found to increase linearly with amplitudes from 0.58 to 17.41 D in the two monkeys. The results suggests that the rate of EW stimulated accommodation is dictated by the amplitude. We conclude that if dynamic accommodative responses are to be compared in monkeys of different ages it is necessary to compare responses for the same accommodative amplitudes in order to draw conclusions about age related changes. © 2002 Published by Elsevier Science Ltd.

Keywords: Infrared photorefraction; Dynamic optometer; Time constants; Refraction; Lens

1. Introduction

Accommodation is a dynamic, dioptric change in power of the eye. In humans, push-up tests are generally used as a clinical measure of accommodation. This requires the subject to report when the smallest legible letters of a near reading chart can no longer be held in sharp focus as the chart is moved towards the eyes. Accommodative amplitude in diopters (D) is determined as the reciprocal of the near reading distance measured in meters. This test does not measure true accommodative amplitude since it cannot distinguish between a change in dioptric power, depth of focus or multifocality such as may result from ocular aberrations. Objective measures, be they static or dynamic, are more appropriate to assess true accommodative amplitude. While static measures can provide assessment of maximum accommodation, they may be subject to inaccuracies when accommodation is changing dynamically. Dynamic, objective measurement can provide more accurate measures of accommodative amplitude as well as information such as rates, time constants and how these may change with accommodative amplitude and age. Dynamic analysis also allows comparisons between accommodation and disaccommodation.

Considerable information on accommodation is available from dynamic measures. In humans, dynamic infrared (IR) optometers (Campbell & Robson, 1959; Charman & Heron, 1975; Cornsweet & Crane, 1970; Kruger, 1979; Cumming & Judge, 1986) and video based systems (Schaeffel, Wilhelm, & Zrenner, 1993) have been used both experimentally (Stark & Atchison, 1997; Culhane & Winn, 1999; Heron, Charman, & Gray, 1999) and clinically (Thal, Phillips, & Stark, 1977; Sun & Stark, 1986). Several studies suggest that dynamic accommodative responses change with age (Sun et al., 1988; Schaeffel et al., 1993; Fukuda, Kanada, & Saito, 1990; Temme & Morris, 1989). Heron, Charman, and Schor (2001) point out that many studies use stimuli of different amplitudes for subjects of different ages or use stimuli at or beyond the range of older subjects. When a low accommodative amplitude within the range of all subjects is used, no age-related changes are evident (Heron et al., 2001). Age-related changes in dynamic aspects of accommodation other than refraction have also been reported. Continuous ultrasound biometry in

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* Corresponding author. Tel.: +1-713-743-1876; fax: +1-713-743-2053.

E-mail address: aglasser@popmail.opt.uh.edu (A. Glasser).

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humans (Beers & van der Heijde, 1996) and gonioscopically viewed lens and ciliary processes movement in monkeys (Croft et al., 1998) suggest age-related changes. However, lens time-constants from ultrasound biometry were found to be age dependent for stimuli at the same accommodative demand (Beers & van der Heijde, 1996). Comparisons of rates for maximum available amplitude or comparisons at different accommodative amplitudes assume that rate is independent of amplitude. If rate of accommodation changes with accommodative amplitude, comparisons across age for different amplitudes may be inappropriate.

Several studies, although not all in agreement, suggest that accommodative rates change with amplitude (Allen, 1956; Hung & Ciuffreda, 1988; Ciuffreda & Kruger, 1988) and that dynamics are different for the same accommodative amplitude at different distances i.e., 4 D between 0.6 and 4.6 D vs 4 D between 4.6 and 8.6 D (Beers & van der Heijde, 1994). Studies have also shown that rates differ between accommodation and disaccommodation (Allen, 1956; Beers & van der Heijde, 1994; Croft et al., 1998).

Thus, accommodation dynamics can be compared across ages for (i) maximum available amplitude, (ii) for stimuli at the same distance or (iii) for stimuli at different distances but the same accommodative range. If the maximum amplitude or a fixed proportion of total available amplitude of each subject is used, different absolute amplitudes are compared for each subject. If a fixed amplitude that is within the range of all subjects is used, this represents a higher proportion of the total available amplitude for older subjects. It is not clear what the appropriate comparison should be to ascertain age dependent changes.

In rhesus monkeys, accommodation can be achieved behaviorally (Smith & Harwerth, 1984), pharmacologically (Koretz, Bertasso, Neider, True-Gabelt, & Kaufman, 1987; Kaufman, Bito, & DeRousseau, 1982; Crawford, Terasawa, & Kaufman, 1989) or through EW stimulation (Koretz et al., 1987; Crawford et al., 1989). Ultimately, behavioral experiments are necessary to understand the true nature of voluntary accommodation, however there is much to be learned from studying pharmacologically or EW stimulated accommodation in anesthetized monkeys. Pharmacological stimulation can be used to determine maximum amplitude, but response times are slow and dictated by pharmacodynamics. EW stimulation is a method of reliably eliciting accommodation in monkeys (Crawford et al., 1989) that is well suited for studies of accommodative dynamics (Croft et al., 1998; Glasser & Kaufman, 1999).

Young monkeys have high accommodative amplitudes relative to humans as assessed behaviorally (15–18 D), pharmacologically (20–34 D), or from EW stimulation (10–27 D) (Table 1) and a similar accommodative mechanism to humans (Glasser & Kaufman, 1999) and therefore represent an excellent species for studies of dynamic accommodation.

EW stimulated accommodation in anesthetized monkeys is open-loop accommodation since it does not rely on visual feedback to diminish an error signal or to match demand with response. Behaviorally, target driven or reflex accommodation to reduce retinal image blur and maximize retinal image contrast, is closed-loop since it relies on visual feedback for response to match demand. Voluntary accommodation in the absence of a stimulus (such as in the dark or due to convergence) is also open-loop, since no visual matching between stimulus and response occurs (Ciuffreda & Kruger, 1988; Heron et al., 2001). In EW stimulated accommodation in monkeys, the amplitude of the stimulus delivered to the brain dictates the extent of current spread at the

Table 1
Accommodative amplitudes as reported in the literature for various species of monkeys as assessed behaviorally, pharmacologically and from EW stimulation

Method of assessment	Max amplitude (D)	Age	Species	Reference
Behaviorally	17–18	18 and 19 month old	Rhesus (*Macaca mulatta*)	Smith and Harwerth (1984)
Behaviorally	15–17	17 to 30 month old	Pigtailed macaques (*Macaca nemestrina*)	Kiorpes and Boothe (1984)
Pharmacologically	~20	Not given	Cynomolgus (*Macaca irus*) and vervet (*Cercopithecus ethiops*)	Törnqvist (1964, 1965, 1966)
Pharmacologically	~22	7 and 8 year old	Rhesus (*Macaca mulatta*)	Koretz et al. (1987)
Pharmacologically	~34	1 to 5 year old	Rhesus (*Macaca mulatta*)	Bito, DeRousseau, Kaufman, and Bito (1982)
Pharmacologically	15–20	Young	Rhesus (*Macaca mulatta*)	Crawford et al. (1989)
EW stimulation	10–27	Not given	Night (*Aotua trivigatus*) or cynomolgus (*Macaca irus*) monkeys	Chin, Ishikawa, Lappin, Davidowitz, and Breinin (1968)
EW stimulation	~18	7 and 8 year old	Rhesus (*Macaca mulatta*)	Koretz et al. (1987)
EW stimulation	10–14	Young	Rhesus (*Macaca mulatta*)	Crawford et al. (1989)

bipolar electrode tip and therefore the number of EW neurons that are recruited and stimulated. Accommodative amplitude and presumably rate are therefore dictated by the number of neurons recruited and the mechanics of the intraocular accommodative apparatus, but not at all by visual feedback, thus also representing open-loop accommodation. While differences between the dynamics of open- vs closed-loop accommodation might be expected, none were found when accommodative response amplitude vs peak velocity were compared between several conditions of reflex and voluntary accommodation in humans (Ciuffreda & Kruger, 1988).

Studying the dynamics of open-loop accommodation may be useful for identifying the mechanics of the accommodative plant (i.e., the ciliary muscle, ciliary body, lens, capsule, etc.) and potential age-related changes which lead to presbyopia. Accommodation in the lens occurs by virtue of changes in thickness and surface curvature through the capsular forces on the lens substance. Age-related changes in lens hardness, viscosity and ability to undergo optical changes with mechanical stretching (Glasser & Campbell, 1998; Glasser & Campbell, 1999) or age-related changes in the extralenticular accommodative apparatus (Lutjen-Drecoll, Tamm, & Kaufman, 1988; Neider, Crawford, Kaufman, & Bito, 1990; Tamm, Tamm, & Rohen, 1992) suggest that there may be age dependent changes in the dynamics of accommodation.

Dynamics of various aspects of accommodative function have been studied with respect to age in rhesus monkeys (Neider et al., 1990; Croft et al., 1998). These studies concentrated on mechanics of the movements of the accommodative structures rather than on changes in dioptric power of the eye. Dynamic accommodative optical changes have been measured in awake behaving monkeys (Cumming & Judge, 1984; Cumming & Judge, 1986; Flitcroft, Judge, & Morley, 1992) but only relatively low amplitudes were tested and rates are not available from these studies. No previous studies have reported the relative rates of accommodation and disaccommodation per diopter over the full accommodative range in monkeys.

We have undertaken this study to characterize EW stimulated optical accommodative dynamics in young rhesus monkeys using dynamic IR photorefraction. This provides a comparison of rates of accommodation and disaccommodation (near to far accommodation) as a function of accommodative amplitude. This groundwork represents a first step towards utilizing measures of the dynamic accommodative optical response to understand how rhesus monkey accommodative dynamics are affected by the progression of presbyopia.

The aims of this study were: (1) to compare pharmacological versus EW stimulated accommodative amplitude, (2) to use IR photorefraction to measure dynamic accommodation in monkeys, (3) to characterize the dynamic EW stimulated accommodative responses, (4) to assess the relative rates per diopter of accommodation and disaccommodation, and (5) to assess the accommodative response to repeated stimulation in two monkeys.

2. Methods

2.1. Monkeys

All experiments conformed to the ARVO statement for the use of animals in ophthalmic and vision research and were in accordance with institutionally approved protocols. Two rhesus monkeys, #4 and #85 (*Macaca mulatta*), ages nine and eight years respectively were used. The monkeys had previously undergone bilateral, complete iridectomies (Kaufman & Lutjen-Drecoll, 1975), assessment of maximum pharmacologically stimulated accommodative amplitude (see below) (Koretz et al., 1987) and surgical implantation of a stimulating electrode into the EW nucleus (Crawford et al., 1989). During surgery, electrode placement was verified with stereotaxic X-ray ventriculography (Crawford et al., 1989) and by comparing the accommodative response with that from prior pharmacological stimulation. When the electrode tip was within 3 mm of the putative EW nucleus site a Hartinger coincidence refractometer was used to determine accommodative responses during stimulation. While stimulating, the electrode position was adjusted until a maximal and symmetric, binocular accommodative response approaching the pharmacologically stimulated amplitude was achieved.

2.2. Carbachol iontophoresis

Carbachol was applied iontophoretically to determine the maximum amplitude and time course of pharmacologically stimulated accommodation. Each monkey was anesthetized with intramuscular ketamine, (Ketaset, Fort Dodge Animal Health, Fort Dodge, Iowa); 10 mg/ kg and Acepromazine, (Vedco, INC. St. Joseph, MO); 0.5 mg/kg. The monkeys were placed in a head holder and baseline resting refractions were measured with a Hartinger coincidence refractometer (Zeiss, aus JENA). Plano, rigid, gas permeable contact lenses were placed on both corneas and refractions were measured again. The following procedure was then performed in both eyes separately. The contact lens was removed and 40% carbachol (Sigma) in an agar gel was iontophoretically applied to the central cornea for 5 s (Koretz et al., 1987). The cornea was immediately irrigated, the contact lens replaced and at one minute intervals refraction was measured three times until no further change was observed at three consecutive 1-min intervals. To determine if maximum accommodation was achieved, carbachol was again applied iontophoretically for three seconds and refraction measurements were repeated for 5 min or until no further change in refraction occurred. Accommodation was determined as the mean baseline resting refraction with the contact lenses in place subtracted from the mean of the three refraction measurement at each 1-min interval.

2.3. EW stimulated accommodation

To study EW stimulated accommodation, monkeys were anesthetized with intramuscular ketamine, (Ketaset, Fort Dodge Animal Health, Fort Dodge, Iowa); 10 mg/kg and acepromazine, (Vedco, Vedco, INC., St. Joseph, MO); 0.5 mg/kg and surgical depth anesthesia was induced with sodium pentobarbital (Nembutal; Veterinary Laboratories, INC., Lenexa, Kansas); 15 mg/kg intravenously, with supplements of 10 mg/kg hourly or as required.

The anesthetized monkeys were placed prone with the head held in a head holder upright and facing forward. 4-0 nylon sutures were passed beneath the lateral and medial rectus muscles with light tension to restrict eye movements. A plano, rigid, gas-permeable contact lens was placed on the cornea and baseline resting refractions were measured with a Hartinger coincidence refractometer (Zeiss, aus JENA).

2.4. EW stimulated accommodation response functions

To characterize the accommodative response functions of each monkey the following procedure was performed. Accommodation was stimulated using 2-s long stimulus trains (frequency: 71.42 Hz; pulse width: 600 μs). EW stimulated accommodative response functions were measured at the start of each session for each monkey (Crawford et al., 1989). The procedure was first performed in its entirety for one eye and then repeated for the second eye.

During each 2-s long stimulus train the maximum accommodative response was measured with the Hartinger. While stimulating accommodation the Hartinger was manually adjusted to compensate the scissoring of the mires as accommodation occurred and the most negative refraction was recorded. Stimulus amplitude was gradually increased from zero in steps of 40 μA until three consecutive, increasing stimulus amplitudes produced no further increase in accommodation. This process was repeated to yield an EW stimulated accommodation response function for the left and right eye of both monkeys. To determine if increasing versus random order stimulations produced similar accommodative responses, the EW stimulated accommodation response functions were repeated using a random sequence of stimulus amplitudes for each eye.

2.5. Dynamic measures of accommodation using infrared photorefraction

To measure dynamic changes in refraction during EW stimulated accommodation, IR photorefraction was used (Schaeffel et al., 1993; Glasser & Kaufman, 1999). A custom made photorefractor consisting of 20 IR LEDs (890 nm) was mounted on a 55 mm lens on a CCD camera. The video signal was recorded on videotape overlaid with a signal from a VSI-Pro (Trans-American International, Inc.) to register a 00 or a 11 on each video frame to indicate if the stimulus was off or on respectively. Subsequently, off-line, a PC-based system with Optimas image analysis software (Media Cybernetics, Silver Springs, MD) was used advance the VCR, capture and analyze sequences of images from the videotape. The software located the Purkinje image, determined the pupil diameter and measured the vertical brightness profile through the pupil in each video frame (Schaeffel et al., 1993). Since the eyes were iridectomized, pupil diameters were unchanged and were not considered further.

To use photorefraction to measure accommodation, it was first necessary to calibrate it (Schaeffel et al., 1993) (Fig. 1). To ensure accuracy, a unique calibration was performed and used for each eye of each monkey. The first EW stimulated accommodation response function obtained with the Hartinger coincidence refractometer (as described above) identified the stimulus amplitude required to produce a particular refractive state (Fig. 1A). Eight increasing stimulus amplitudes were selected that covered the full accommodative range of each eye. For each stimulus amplitude, a sequence of 3, 2-s long stimulus trains was delivered and the IR photorefractive responses were recorded. Photorefraction calibrations were initially performed at working distances of 0.5 and 0.3 m. In all subsequent experiments a 0.3 m working distance was used. The slope of the pupil brightness profile (Schaeffel et al., 1993) was measured in one frame in the eye when unaccommodated (Fig. 1B and C) and then in one frame towards the end of each 2-s long stimulus train when near maximum accommodation was anticipated (Fig. 1D and E). This was done for each of the three stimulus trains. The average of three slope measurements at each of eight stimulus amplitudes allowed a mean pupil brightness slope vs refraction calibration function to be plotted (Fig. 1F). Linear regressions were fitted to these functions except in the case of monkey #4 OD where a second order polynomial was used. The regression lines provided unique photorefraction calibration curves relating the slope of the pupil brightness profile to refraction for each eye of each monkey. These were used to convert measured slope to refraction in all subsequent analyses. In addition, the brightness of the fundus reflex was measured as the mean brightness along the vertical brightness profile,

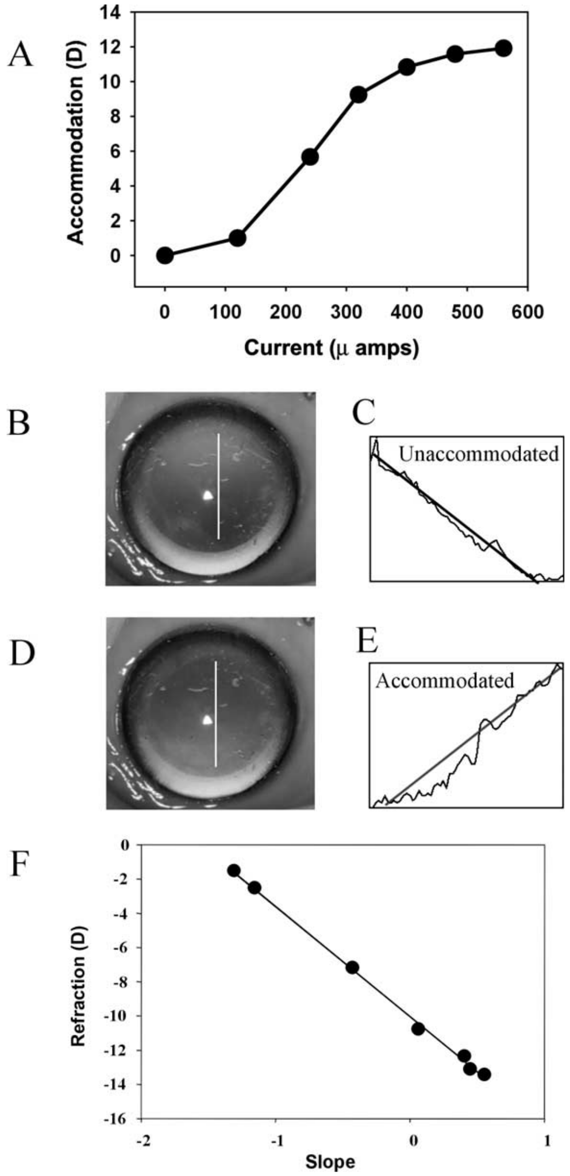

Fig. 1. Procedure for obtaining EW stimulated IR photorefraction calibration functions. (A) Accommodative stimulus response curve measured with a Hartinger coincidence refractometer in monkey #85 OD when increasing stimulus currents are delivered to the EW nucleus. (B) IR photorefraction image of monkey #85 OD with no current delivered, i.e., at baseline refraction. (C) Regression line through the vertical pupil brightness profile provides a slope corresponding to this refractive state. (D) With a stimulus delivered to the EW nucleus there is a change in the refractive state of the eye towards more myopic refraction (increased accommodation) and (E) the pupil brightness profile changes accordingly. The bright crescent at lower margin of the eye is refraction of IR light from the base curve of the contact lens outside of the optic zone and is not considered in the analysis. For panels C and E, *x*-axis is vertical position in the pupil and *y*-axis is pixel luminance. Vertical luminance profiles across the pupil are measured at eight different refractive states (stimulus amplitudes) starting from baseline to the highest amplitude of accommodation and (F) a slope vs refraction calibration curve obtained. The regression line fitted to this calibration curve is subsequently used as the IR photorefraction calibration curve for this eye.

in the unaccommodated and maximally accommodated states.

2.6. Accommodation stimulation tests performed

2.6.1. Repeatability of EW stimulation

The consistency of the EW stimulated accommodative responses within a single session were assessed as follows. An EW stimulated accommodation response function was measured with the Hartinger for each eye of each monkey at the start and then three more times at various intervals during the single 3–4 h session. The same stimulus amplitudes were used each time. Two of these EW stimulated accommodation response functions were measured before the accommodation/disaccommodation test (described below) and one each before and after the fatiguing tests (also described below).

2.6.2. Rates of accommodation and disaccommodation

Rates of accommodation and disaccommodation for different accommodative amplitudes were assessed as follows. For each eye of each monkey, five different stimulus amplitudes were selected to produce five different accommodative responses spanning the full EW stimulated accommodative range. Dynamic IR photorefractive measures of accommodation were recorded for these five amplitudes by delivering 3, 4-s long stimulus trains at each of the five stimulus amplitudes. The slope of the vertical pupil brightness profile was measured in each frame from 20 frames before the stimulus onset to 37 frames after the stimulus terminated. This allowed analysis of the resting refraction preceding the stimulus and sufficient time following the stimulus for the eye to reach a baseline refraction again. Slope measurements were then converted to absolute refraction using the calibration curves. Refractions from the first frame of each of the three traces were averaged to obtain the baseline resting refraction.

Accommodation was determined for each frame as the difference between the baseline refraction and the measured refraction. This procedure provided three dynamic accommodation responses recorded at a frequency of 30 frames per second at five stimulus amplitude for each eye.

2.7. Analysis of the accommodation and disaccommodation responses

The time from stimulus onset to termination provided the *accommodation phase*. The remaining portion of the trace constituted the *disaccommodation phase*. Initially the accommodation and disaccommodation phases were modeled with first-order or pure exponential accommodation and disaccommodation equations (Beers & van der Heijde, 1994). These equations did not adequately describe accommodative responses in which the maximum amplitude was not maintained throughout the stimulus duration. For this reason, the accommodation and disaccommodation phases were subsequently modeled with equations comprised of first order and quadratic components.

Accommodative phases of the dynamic accommodative response were well fit with:

$$F = A\left(1 - \mathrm{e}^{-x/\tau}\right) + bx + cx^2 \qquad (1)$$

and disaccommodation phases were well fit with:

$$F = A\left(\mathrm{e}^{-x/\tau}\right) + bx + cx^2 \qquad (2)$$

where $x =$ time, $\tau =$ time constant of accommodation, $A =$ maximum (for accommodation) or minimum (for disaccommodation) refraction, and b and c are constants particular to each specific response. To fit the traces and do statistical analyses (described below), the data from three successive responses recorded at the same stimulus amplitude were *collapsed* into a single data set (rather than averaging the three responses). The above equations were then fit to the collapsed data. Derivatives of these functions with respect to time were calculated. The maximum and the minimum of the derivative as a function of time provided the maximum rate of accommodation and the maximum rate of disaccommodation respectively. The maximum rates of accommodation and disaccommodation were compared as a function of the amplitude of the accommodative response.

Time constants of accommodation and disaccommodation were obtained from Eqs. (1) and (2) at each amplitude in each eye. Time constants were compared as a function of the absolute accommodative amplitude.

2.8. Fatiguing

To test if fatiguing occurred and whether accommodation could be maintained for longer than 4-s stimulus durations, the following test was performed. Accommodation was stimulated in each monkey 10 times for a stimulus duration of 6 s using the stimulus amplitude that produced the maximum accommodative response, with an inter-stimulus interval of 60 s. IR photorefractive measures of dynamic accommodation were recorded from the right eye only of each monkey.

2.9. Statistics

To determine if Eqs. (1) and (2) adequately fit the accommodative and disaccommodative responses, a lack of fit test (Weisberg, 1985) was performed on the collapsed data from three stimulus trains for each stimulus amplitude in each eye. P-values were calculated with the null hypothesis that the model provides a significant fit to the data. p-Values greater than 0.05 show that the regressed equations are not significantly different from the data while p-values less than 0.05 show that the equation was significantly different from the data. When the lack of fit test showed that the data were inadequately fit, local regressions were performed (S-PLUS 2000 Guide to Statistics) to obtain rates of accommodation and disaccommodation. Local regression is a locally weighted regression smoother, fitting a curve to the data points locally. At any point the curve depends only on the observations at that point and specified neighboring points by weighted least square regression. Since there are no restrictions on the forms or relationships between responses and predictors, local regression models provide great flexibility compared to equation-forced fitting techniques. No mathematical expression is available for the fitted curve from local regression procedures, but a peak velocity can be obtained.

3. Results

3.1. Carbachol iontophoresis

Carbachol iontophoresis was used to determine maximum accommodative amplitude, to determine the time course of the response and to establish what is required to ensure that maximum accommodation is achieved. The time course of carbachol iontophoresis induced accommodation was slow, variable between individual eyes of the same monkey and between monkeys (Fig. 2). The maximum pharmacologically stimulated accommodative amplitudes were similar between eyes for the same monkey, but different for the two monkeys. Monkey #4 had a longer latency following drug administration but a faster response than monkey #85. The efficacy of the pharmacological administration varied. Both eyes of monkey #4 achieved near maximum accommodation from the first carbachol administration (Fig. 2A and B) whereas OD of monkey #85 required a second administration to achieve maximum accommodation (Fig. 2C and D). Despite variation in response times and the need for additional drug applications in some instances, this approach ensured that maximum accommodation was achieved.

3.2. EW stimulated accommodation response functions

From the first EW stimulated accommodation response function measured with the Hartinger, monkey #4 achieved 15.67 D OD, but only 14.00 D OS. Monkey #85 achieved 10.83 D OD and 11.92 D OS (Fig. 3). The stimulus currents required to achieve maximum accommodation, while similar for the two eyes of #85, differed between the two eyes of monkey #4 with OS having a steeper response function than OD.

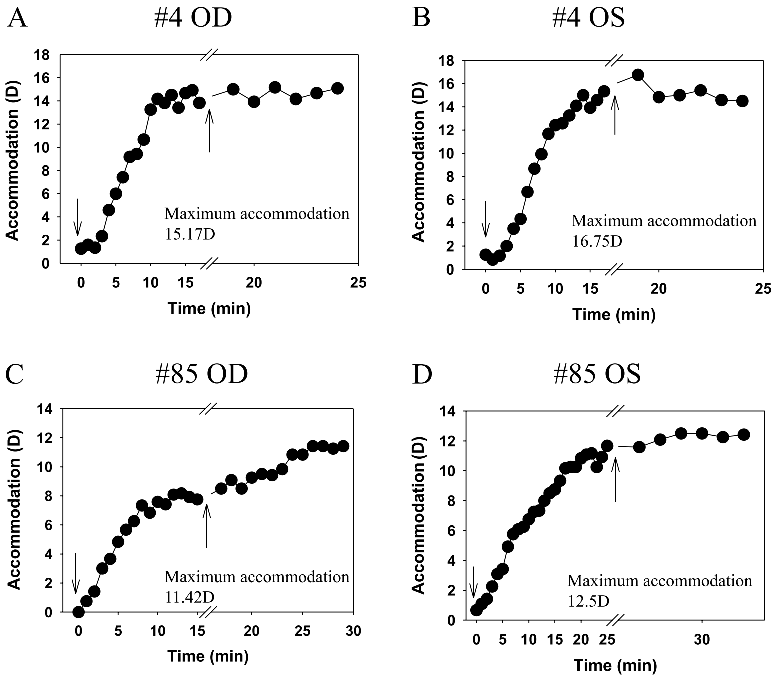

Fig. 2. Carbachol iontophoresis induced accommodation for the two eyes of the two monkeys. Carbachol was applied iontophoretically to the central corneal apex for 5 s (downward pointing arrows). Refraction was then measured three times at 1 min intervals with a Hartinger coincidence refractometer. Once accommodation had reached a stable level for three successive measures, carbachol was again iontophoretically applied for a further 3 s (upward pointing arrows). Refraction was again measured for 5 min or until maximum accommodation was attained.

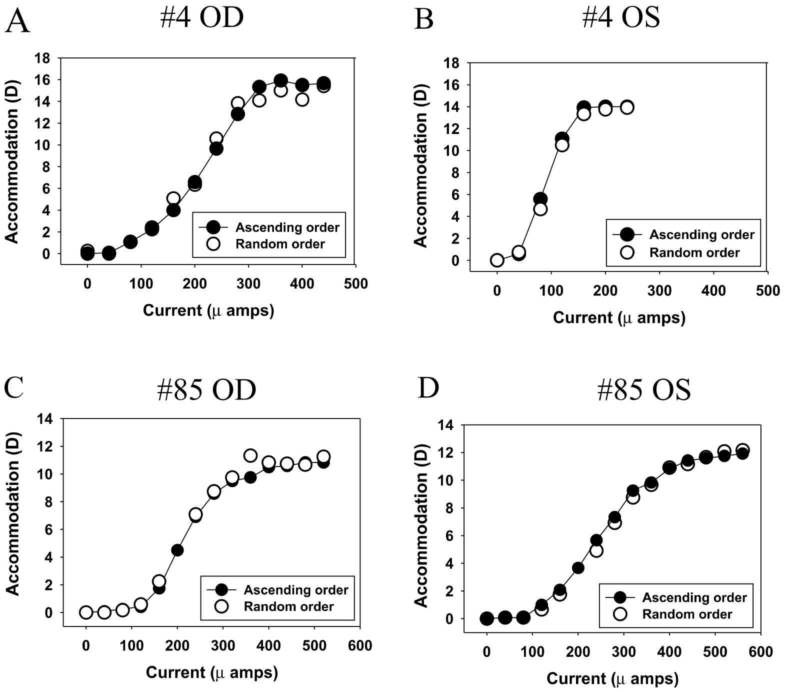

Fig. 3. Initial EW stimulated accommodation response functions of the two eyes of the two monkeys as recorded at the start of each experimental session (line and solid symbols). Subsequently, a second EW stimulated accommodation response function was generated with random order stimulations (open symbols) employing the same stimulus amplitudes. For monkey #4 OS and OD, the maximum accommodative amplitudes are achieved at different stimulus currents and result in slightly different accommodative amplitudes. The stimulus response curves are similar between the two eyes from monkey #85.

For both monkeys, a second, subsequent EW stimulated accommodation response function obtained using a random sequence of stimulus amplitudes shows little variation from the initial function obtained with sequentially increasing stimulus amplitudes (Fig. 3).

From the average of the four EW stimulated accommodation response functions measured with the Hartinger (Fig. 4), both eyes of each monkey achieved roughly the same accommodative amplitude. Monkey #4, the older monkey, had a slightly higher amplitude than monkey #85. The variance in the accommodative amplitudes recorded at different times within the same experimental session are shown by the extent of the error bars (standard deviations) in Fig. 4.

3.3. Infrared photorefraction

IR photorefraction calibration curves were initially determined at a working distance of 0.5 m. These were nonlinear and steeper at higher accommodative amplitudes (Fig. 5A). A closer working distance of 0.3 m provided curves that were linear over the full range of the accommodative responses. The calibration curves obtained at 0.3 m were different between the two monkeys, but similar between the two eyes of each individual monkey. Mean pupil brightness differed substantially between the two monkeys and mean pupil brightness differed slightly with refraction within the same eye (Fig. 5B).

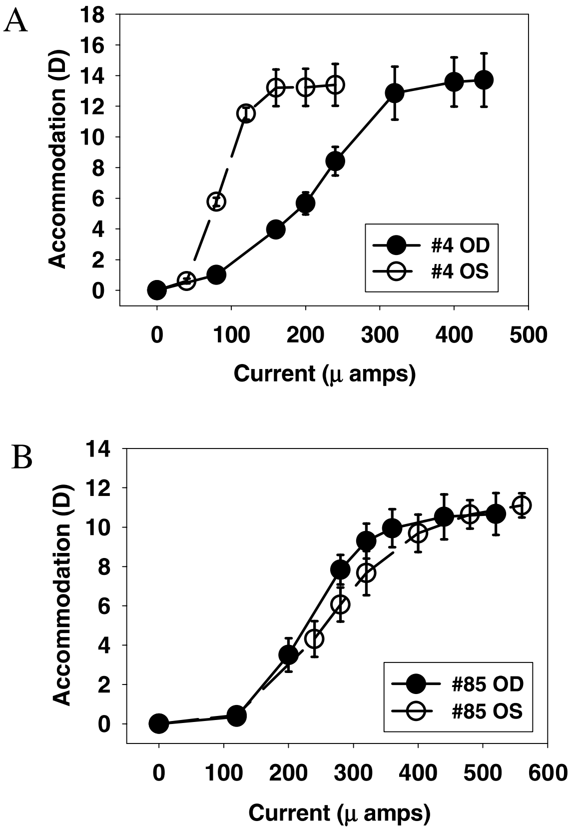

Fig. 4. EW stimulated accommodation response functions were measured with a Hartinger at the start and then three more times during a single session on each eye of each monkey to assess the variability of the accommodation responses within a session. The same stimulus amplitudes were used on each occasion. Variation in accommodative amplitudes that were recorded at different times are shown by the extent of the error bars (standard deviations). On average, the accommodative amplitudes achieved for both eyes of each monkey were the same, despite small differences observed for individual EW stimulated accommodation response functions (see Fig. 3).

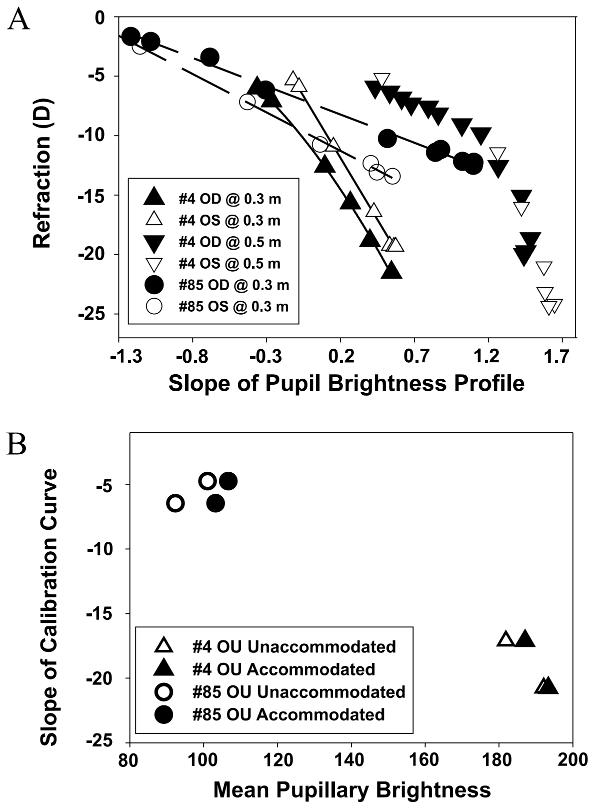

Fig. 5. (A) IR photorefraction calibration functions for the two eyes of the two monkeys. The graph shows refraction (y-axis) as recorded with a Hartinger coincidence refractometer graphed as a function of the slope of the pupil brightness profile (x-axis) as obtained from IR photorefraction. Monkey #4 (triangles) was recorded at two distances (inverted triangles: 0.5 m and upright triangles: 0.3 m) while monkey #85 (circles) was recorded only at 0.3 m. Recordings at 0.3 m (symbols with lines) show good linearity over the full range of accommodative amplitude (in the case of right eye of #4 a second order polynomial was used). A 0.5 m working distance for monkey #4 (inverted triangles) showed nonlinearities that precluded use of these calibration curves. All subsequent experiments were performed at 0.3 m and the linear calibration curves were used to convert the slope of the pupil brightness profile to refraction. The calibrations at 0.3 m are similar in the two eyes of each monkey but are quite different between monkeys. (B) Mean pupillary brightness was calculated as average pixel brightness along the vertical line through the pupil. Circles represent the two eyes of monkey #85 and the triangles represent the two eyes of monkey #4. There is a striking difference in the mean pupillary brightness between the two monkeys which may explain the difference in the IR photorefraction calibration curves obtained. However there is little difference in the mean pupillary brightness between the two eyes of a monkey and between accommodated and unaccommodated states within an eye.

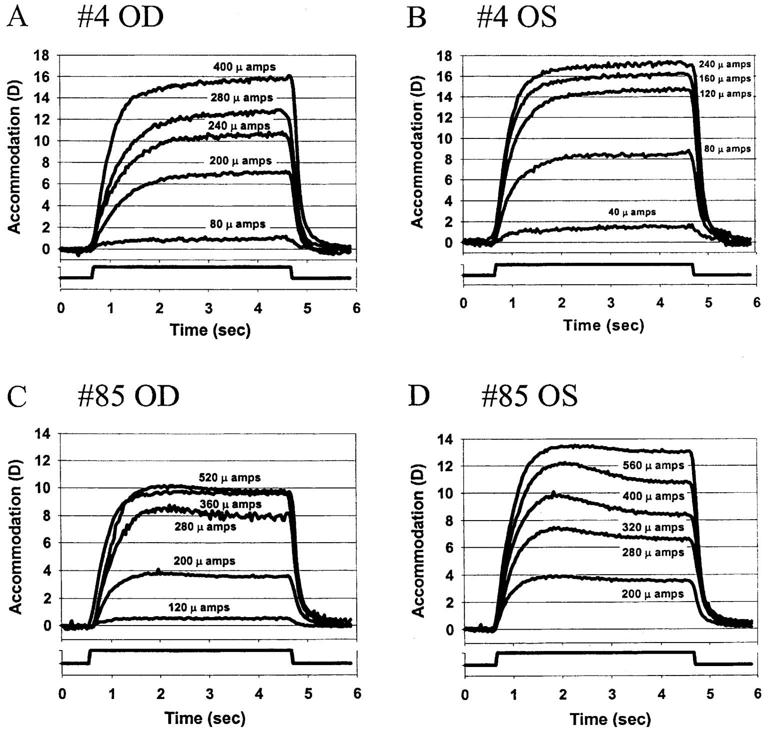

Fig. 6. Five dynamic accommodative responses each for monkey #4 OD (A) and OS (B) and monkey #85 OD (C) and OS (D) with low to high stimulus amplitudes encompassing the full range of the EW stimulated accommodative amplitude available to each eye. The solid line at the bottom of each graph represents the stimulus onset, duration and termination.

IR photorefractive traces of dynamic accommodation for the two eyes of the two monkeys indicate some variability in the accommodative responses between monkeys and differences at different stimulus amplitudes for the same eye (Fig. 6). For example, at stimulus amplitudes of 320 and 400 μA monkey #85 OS shows a maximum accommodative response early in the stimulus train and a decrease thereafter, however responses at higher and lower stimulus amplitudes differed for this same eye.

3.4. Comparing amplitude of pharmacological and EW stimulated accommodation

Accommodative amplitude differed with pharmacological and EW stimulation and between Hartinger and photorefractor measurements. In general, the initial EW stimulated accommodative amplitudes as measured with the Hartinger at the start of each session were similar to those obtained with carbachol iontophoresis in a prior session (Table 2; Figs. 2 and 3). This provides verification of appropriate electrode positioning to obtain maximum responses. Two objective methods were used to measure EW stimulated accommodation and some variability was observed. Monkey #4 OS (Fig. 6B) had a higher EW stimulated accommodative amplitude as measured with IR photorefraction than that measured with the Hartinger in the first EW stimulated accommodation response function in the same session (Fig. 3b). Monkey #85 OD had a slightly lower EW stimulated amplitude when measured dynamically with IR photorefraction than that measured with the Hartinger from the initial EW stimulated accommodation response function. The average EW stimulated accommodative amplitudes were lower than the maximum pharmacologically stimulated amplitudes for both monkeys (Fig. 4) suggesting that pharmacological stimulation of accommodation is the most effective method to stimulate maximum accommodation.

Table 2
Comparison of the maximum amplitudes of accommodation obtained from each eye of each monkey using pharmacological and EW centrally stimulated accommodation

Monkey eye	Pharmacological stimulation (D)	EW stimulation Hartinger (D)	EW stimulation IR photorefraction (D)
#4 OD	15.17	15.67	16.09
#4 OS	16.75	14.00	17.41
#85 OD	11.42	10.83	10.18
#85 OS	12.50	11.92	13.53

3.5. Fitting accommodative functions

Eqs. (1) and (2) described the accommodative and disaccommodative phases of all responses reasonably

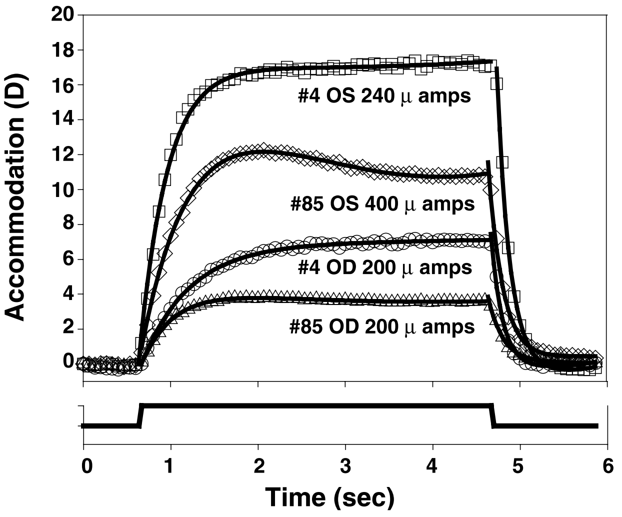

Fig. 7. Four different accommodative responses from four different eyes of the two monkeys used. Open symbols show the average instantaneous accommodative amplitude (from three recorded responses) at every second image frame for the accommodation and disaccommodation phases. The data from intervening image frames was skipped to reduce the density of the symbols to see the underlying lines. The solid lines show Eqs. (1) and (2) fit to the data for accommodation and disaccommodation phases. These equations provide good descriptions of the accommodation and disaccommodation phases including the nonlinearities therein. The solid line at the bottom of the graph represents the stimulus. The equations for accommodative phase of #4 OS 240 μA and the disaccommodative phase of #85 OS 400 μA did not attain statistical significance, but the equations for the other two traces did. Qualitatively, there is no discernable difference between the fits.

well despite individual differences in the characteristics of the responses (Fig. 7). In most cases, the equations fit the data well as determined by the lack-of-fit test.

In one out of 20 accommodative traces (#4, OS at 240 μA, $p = 0.0012$) and three out of 20 disaccommodative traces (#4, OD at 400 μA, $p < 0.0001$; #85, OS at 200 μA, $p = 0.0387$ and 400 μA, $p = 0.0084$) the equations were significantly different from the data. While the fits in these four cases were subjectively no different from any others (Fig. 7), the statistical evaluation was used to determine the goodness of fit. In each of these four cases the three individual responses that were collapsed for the lack-of-fit test showed extremely consistent responses which reveal a significant discrepancy between the selected equation and the data. In these four cases, the failure to fit the data reflects the high demands placed on the equation to match the extremely consistent responses, and rates of accommodation and disaccommodation were obtained using local regressions rather than from the derivatives of the equations. These four rates were not included in any analyses due to the different methods employed. In these four instances, local regressions yielded rates that were lower than those obtained from the derivatives of the equations fit (although not attaining statistical significance) to these four traces (Table 3).

Table 3
Comparison of the maximum rates obtained in the four cases in which the Eqs. (1) and (2) deviated from the accommodation and disaccommodation responses[a]

Eye and stimulus	Rate (D/s) from local regression	Rate (D/s) from derivatives
Accommodation #4 OS 240 μA	40.24	53.81
Disaccommodation #4 OD 400 μA	91.28	120.47
Disaccommodation #85 OS 200 μA	15.28	21.47
Disaccommodation #85 OS 400 μA	41.59	66.43

[a] In these four cases, rates were obtained from local regressions (although no equations are yielded). These rates were found to be lower than the rates obtained from the derivatives of the (nonsignificant) equations fit to these four traces.

3.6. Time constants of accommodation and disaccommodation

To determine if accommodation and disaccommodation time constants changed systematically with accommodative amplitude, time constants obtained from Eqs. (1) and (2) were compared against accommodative amplitude for each eye (Fig. 8). In general, time constants for accommodation increased with increasing accommodative amplitude to about 70% of accommodative amplitude and decrease thereafter. Although the shapes of these relationships were similar for each eye, the absolute values differed between eyes. Time constants for disaccommodation did not show any discernable relationship with maximum amplitude of accommodation and were on average less than those for accommodation

3.7. Rates of accommodation and disaccommodation

Maximum rate of accommodation was 49.81 D/s for an accommodative amplitude of 16.3 D and for disaccommodation maximum rate was 116.49 D/s for an accommodative amplitude of 17.41 D. These maximum rates occurred at the start of the accommodation and disaccommodation responses considered in the fitting process. The maximum rates of accommodation and disaccommodation as a function of the accommodative amplitude are shown in Fig. 9A and B. Both increase linearly with increasing amplitude. A comparison of maximum rate of accommodation vs maximum rate of disaccommodation shows a linear relationship with a slope representing a 2.9 times faster rate of disaccommodation Fig. 10. The intercept of −4.884 is not significantly different from zero ($t = -0.416$, $p = 0.658$).

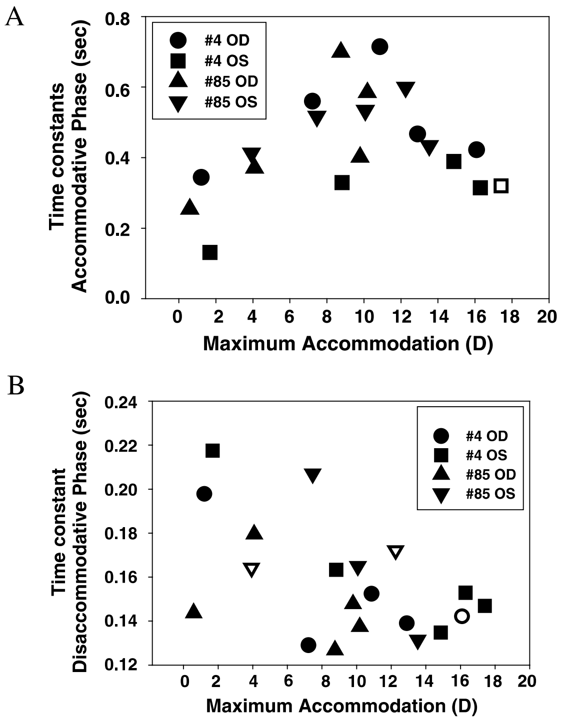

Fig. 8. Time constants for (A) the accommodative phase and (B) disaccommodation phase as a function of the maximum amplitude of accommodation in all the four eyes. Time constants of each eye are represented by different symbols. The solid symbols are from equations that attained statistical significance, the open symbols for those that did not. The time constants for accommodation were found to increase with increasing amplitude to about 70% of the accommodative amplitude and decrease thereafter. Time constants for disaccommodation show no trend with respect to amplitude of accommodation. Time constants of disaccommodation are smaller than those for accommodation.

3.8. Longer duration accommodative responses

For the longer duration stimulus trains, monkey #85 OD showed a stable baseline refraction and consistency in the accommodative response over the 10 min period. Monkey #4 OD had some variability in the resting and accommodated states (Fig. 11A and B). In both cases the accommodative response was maintained for the full duration of the six-second stimulus and no fatiguing occurred (Fig. 11C).

4. Discussion

4.1. Age of monkeys

The two rhesus monkeys used were eight and nine years old. A 4:1 age ratio provides a good description of the relative ages and developmental states for humans and Old World monkeys (Boothe, Donn, & Teller, 1985). This would put the ages of our two monkeys at about 32 and 36 years of age relative to humans. However, Kaufman et al. (1982) suggest that in rhesus monkeys maximum accommodation is achieved at 5–6 years and at 18 years in humans and that rhesus and humans show a relatively stable accommodative capacity by postmenopausal ages 25 and 45 years respectively. This gives the relationship

$$\text{human years} = 1.3846 * \text{monkey years} + 10.385 \tag{3}$$

and suggests our monkeys to be 21.5 and 22.8 year of age relative to humans. The latter relationship is a better estimator of age relative to humans with respect to accommodation, given that the 25 years of age at which accommodation is lost in rhesus monkeys corresponds to 50 years of age in humans rather than 100 years that the 4:1 ratio predicts.

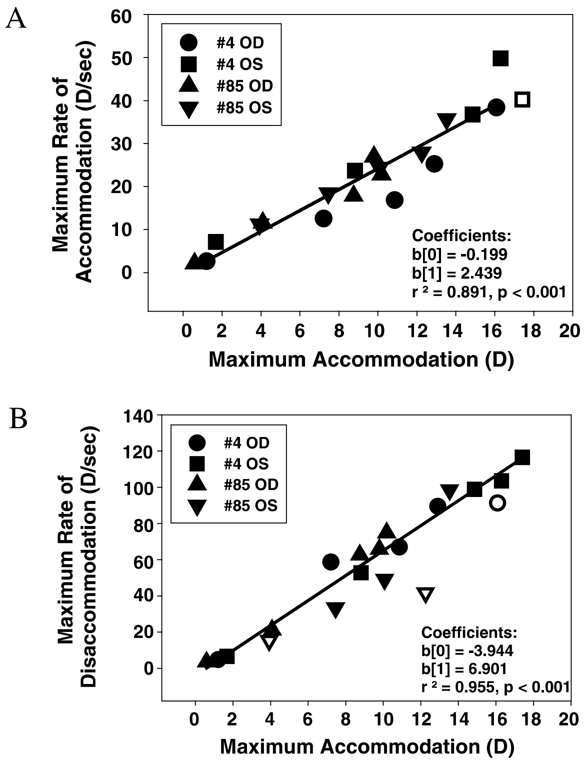

Fig. 9. (A) Rate of accommodation and (B) disaccommodation as a function of accommodative amplitude. The rates of all four eyes of the two monkeys are grouped in these figures. Each eye is represented by a different solid symbol. Rates from equations that did not attain statistical significance are represented by open symbols. The open symbols were excluded from the regression analysis. The coefficients *b*0 and *b*1 represent the intercept and the slope respectively of the regression equations.

4.2. Carbachol iontophoresis

Pharmacological stimulation is necessary to determine maximum accommodation amplitude of monkey eyes (Koretz et al., 1987), to aid in and verify electrode localization (Crawford et al., 1989) and to determine if EW stimulation produces maximum accommodation.

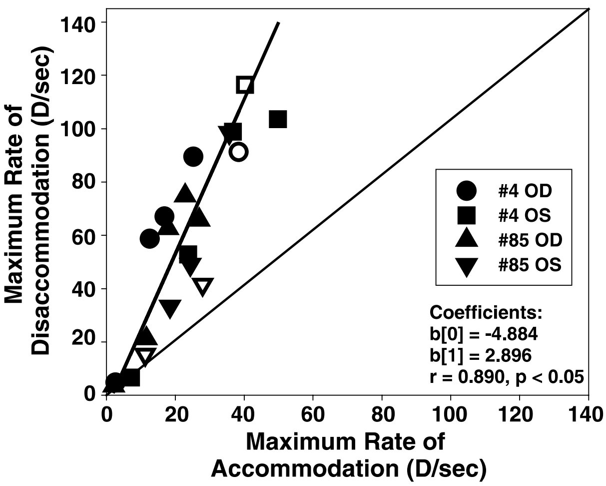

Fig. 10. Rate of disaccommodation vs rate of accommodation for all responses from four eyes of two monkeys. An orthogonal regression is used to fit the data. The rate of disaccommodation is greater than the rate of accommodation. Opens symbols represent rates obtained from dynamic accommodative traces that did not attain statistical significance and were not included in the regression analysis. The coefficients *b*0 and *b*1 represent the intercept and the slope respectively of the regression equations.

Iontophoresis provides better control of the concentration of drug delivery than topical application of drops. However, pharmacological stimulation is not without difficulties. When the iris is present, pharmacological stimulation may produce more accommodation than occurs naturally (Crawford, Kaufman, & Bito, 1990). With iontophoresis, factors such as contact time of the agar gel to the cornea and variations in the gel to cornea contact area may introduce variability in the accommodative response obtained. The need to remove and replace a contact lens to apply the drug and subsequently measure accommodation over prolonged periods introduces variability in the latency at which the first measurement can be made. In addition, pharmacologically stimulated accommodation proceeds slowly, only one accommodation stimulus can be delivered per session, regulation of submaximal amplitude is difficult, disaccommodation can only be studied with pharmacological reversal of accommodation and responses are dictated by intraocular pharmacokinetics rather than physiology of the accommodative process.

4.3. EW stimulated accommodation

While an ideal method for studying dynamic accommodation, EW stimulated accommodation is not without difficulties. Differences in the EW stimulated accommodation response functions between the two eyes of monkey #4 may reflect a midline decentration of the stimulating electrode. While the left eye of monkey #4 had a steeper EW stimulated accommodation response function, on average the amplitudes were similar for the two eyes (Fig. 4). Accurate placement of the stimulating electrode is critical to achieve binocularly symmetric accommodation. An electrode further from the EW nucleus would require a stronger current to achieve maximum accommodation. While the EW stimulated accommodation response function may change with changes in electrode proximity to the EW nucleus, it is likely that maximum accommodation can

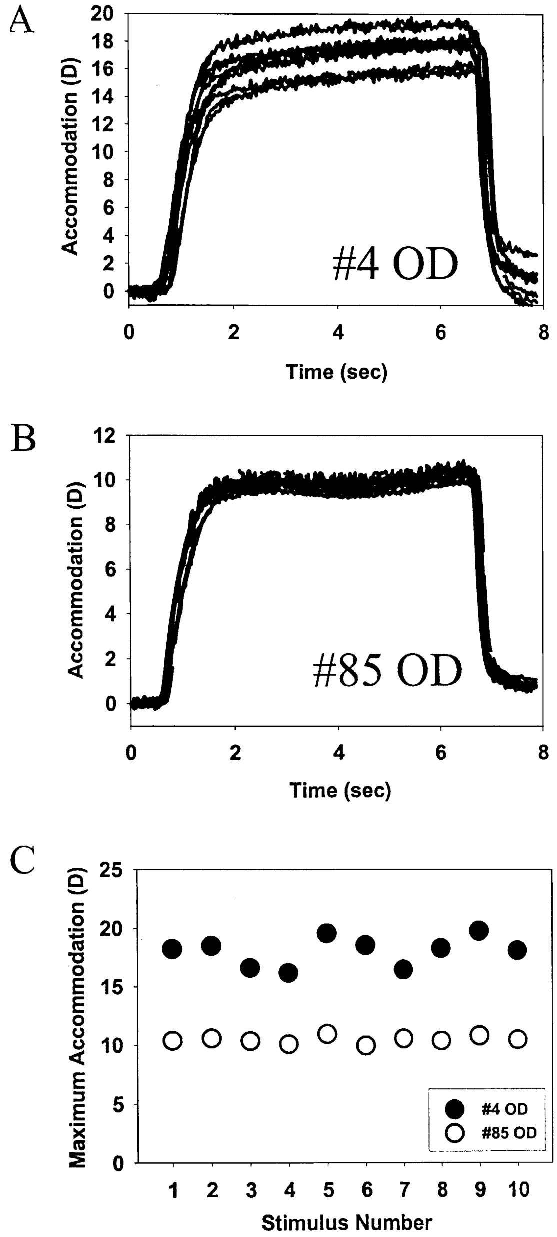

Fig. 11. Accommodative responses in the right eyes of the two monkeys (A and B) to 6 s duration stimuli producing the maximum accommodative amplitudes. Stimuli were delivered at 1 min intervals. (C) Maximum accommodative amplitude achieved for each stimulus for each monkey eye. There is no systematic fatiguing of the accommodative response for 6 s long stimuli, although monkey #4 OD showed some variation in baseline refraction and accommodative amplitude over the stimuli.

be achieved if the electrode is reasonably close. Current spread at the bipolar electrode tip determines the number of neurons recruited. When further from the EW nucleus a greater current will be required to recruit more neurons, but ultimately, with a sufficiently large current, all neurons could be recruited to produce maximum accommodation. It is likely that the different EW stimulated accommodation response functions in this monkey are due to a midline decentration of the electrode that is too small to be visible at the resolution of the X-rays used to verify electrode placement. The different EW stimulated accommodation response functions are unlikely to influence the rate of accommodation.

First, although different currents were used to generate the accommodative responses between the two eyes of monkey #4 and between the two monkeys, the same relationship between amplitude and rate was observed in all eyes (Fig. 9A and B). Second, since the results show that rate of accommodation is governed by amplitude, the rate is therefore not dependent on electrode position, but on the amplitude of the response. Some variability of the EW stimulated accommodation response functions were observed over time (Fig. 4). Although small, this presents some variation in maximum accommodative amplitude during a session. This may be due to variation in level of anesthesia, wandering eye movements that sometimes occur, possible variations in tension on the extra ocular muscles sutures, error in the refraction measurements, or from systemic changes such as blood pressure, intraocular pressure or level of hydration, for example.

To study dynamics of accommodation over the full accommodative range, five different stimulus amplitudes were used. In all but the highest stimulus amplitude for monkey #85 OD (Fig. 6C) there is a systematic increase in accommodative response with increasing stimulus amplitude. In monkey #85 OD the highest stimulus amplitude did not produce the accommodative amplitude anticipated based on the initial stimulus response curve for this eye. EW stimulated accommodation has advantages. Stimulus durations and amplitudes can be rigorously controlled, latencies are short and with little variation and perceptual factors such as target size and brightness, are avoided. However, some variations in accommodative amplitude, in accommodative response at different stimulus amplitudes and in the response between eyes of the same monkey are observed.

Different information is available from behavioral, pharmacological and EW stimulated accommodation. EW stimulated accommodation in monkeys offer unique advantages to study dynamic accommodation, the mechanisms of accommodation and presbyopia and the efficacy of techniques to reverse presbyopia and may represent the only method in which dynamic accommodation can be studied with objective refraction measurements and contact measures such as Scheimpflug, gonioscopy and ultrasound biomicroscopy (Neider et al., 1990; Croft et al., 1998; Glasser & Kaufman, 1999).

4.4. Infrared photorefraction

A 0.5 m working distance produced IR photorefraction calibration curves that were nonlinear with steeper slopes at higher accommodative amplitudes. Such nonlinearities are undesirable and introduce variability in the measured refractions, especially at higher accommodative amplitudes. The linear range for calibration curves obtained in human eyes at a working distance of 1.3 m extends from about +4 to about −4 D (Schaeffel et al., 1993). We sought to extend the linear range to work with the greater accommodative amplitudes of monkey eyes. Adding additional LEDs at increasing eccentricities or decreasing the working distance would increase the range of refractive errors or accommodation that can be measured with photorefraction. Decreasing the working distance has the added benefit of shifting the relative resting refraction towards a more hyperopic state to produce more linear calibration function over the full accommodative range.

IR photorefraction calibration curves obtained at 0.3 m are similar between eyes from the same monkeys, but differ between the two monkeys. In humans, Schaeffel et al. (1993) show that the slope of the calibration function (conversion factor) is dependent on the brightness of the fundus reflex. This in turn depends on pupil diameter and on the reflectivity of the fundus in the IR. Since, for point sources, the brightness of the fundus reflex is proportional to the square of the pupil radius, the brightness of the fundus reflex can be corrected for by pupil diameter. When this correction was applied in humans it was found that the conversion factor was no longer correlated with the brightness of the fundus reflex (Schaeffel et al., 1993). They concluded that the major reason for variability in the conversion factor in humans was variations in pupil diameter. Here, however, the monkeys were iridectomized and the effective pupil size was the same, and unchanging for both monkeys. We found a striking difference in the mean brightness of the pupil profile between the two monkeys, but small difference in brightness between eyes of the same monkey or with accommodative state. The differences in fundus brightness between the two monkeys could be due to differences in the aperture setting of the photorefraction camera lens. This was not controlled or recorded and may have changed. Only when all other factors are controlled can it be conclude that the difference in fundus brightness are due to fundus reflectivity. Whatever the cause of the difference in fundus brightness, the variation provides a possible explanation for the difference in the calibration slopes between the two monkeys.

To use photorefraction to measure dynamic accommodation as accurately as possible we generated individual calibration curves for each eye. Clearly, it is necessary to do this, and possibly necessary to do this each time if fundus brightness is not controlled (such as may occur with different aperture settings) if dynamic accommodation is to be studied accurately in this way.

With EW stimulation, IR photorefraction can be calibrated directly on the eyes while known refractive states (as determined from a Hartinger coincidence refractometer) are stimulated. Prior photorefraction calibrations in humans (Schaeffel et al., 1993; Gekeler, Schaeffel, Howland, & Wattam-Bell, 1997) were generated by holding trial lenses of known power before the eyes. In addition to defocus, the trial lenses alter image magnification and therefore pupil size. The approach we have taken provides a direct comparison between the ocular defocus as measured with the Hartinger coincidence refractometer and photorefraction. To do this it is necessary to first measure the accommodative response at fixed stimulus amplitudes with the Hartinger and then to use the photorefractor at the same stimulus amplitudes. In this way, photorefraction is calibrated against the Hartinger and depends on achieving the same accommodative response each time a given stimulus is delivered. This drawback could be avoided by using a beam splitter to perform the IR photorefraction and the Hartinger measurements simultaneously.

4.5. Time constants of accommodation and disaccommodation

Beers and van der Heijde (1994) showed that time constants of changes in lens thickness increase with increasing stimulus demand between 1 and 4 D. Their time constants were graphed as a function of stimulus rather than response amplitude and represented only about 50% of the accommodative range of their subjects. Here, for monkeys, time constants of accommodation and disaccommodation were obtained for amplitudes spanning the entire accommodative range. For the lower accommodative amplitudes, time constants for dynamic refractive changes in monkeys show similar trends to the time constants obtained from dynamic biometry in humans (Beers & van der Heijde, 1994). In monkeys, time constants of accommodation increase until about 70% of the accommodative amplitude but declined thereafter. Our results also show that time constants for disaccommodation are less than for accommodation and that there is substantial variability in time constants as a function of amplitude for all eyes studied. The peak in time constants with EW stimulated accommodation in anesthetized monkeys at 70% of the accommodative amplitude suggests that this is the amplitude at which the accommodative plant has the slowest response time, at least in these two monkeys. Since the Eqs. (1) and (2) employed to fit the responses include a polynomial component, this may 'dilute' the time constants. However, the nature of the accommodation responses obtained demand that the polynomial component be included since a pure exponential function would not adequately fit the data and would misrepresent different responses in different ways. Interpretation of the time constants reported here and comparisons with other time constants should be done with this in mind. Despite this, the time constants may carry important information. For example, understanding how the relationship between time constants and amplitude may change with increasing age may provide additional insight into the progression of presbyopia in monkeys.

4.6. Rate of accommodation and disaccommodation

In humans, Sun and Stark (1986) show a maximum rate of accommodation of 15 D/s in response to a step change in vergence demand from 1 to 4 D and 8 D/s in response to a step change in vergence demand from 3 to 8 D. For disaccommodation they found 15 D/s for 8 to 5 D and 8 D/s for 4 to 1 D. Two prior studies in humans show a maximum velocity of about 10 D/s for a 2 D step change in vergence demand and indicate that rate increases with accommodative amplitude (Campbell & Westheimer, 1960; Hung & Ciuffreda, 1988). Using the regression from Fig. 9A, the maximum rate corresponding to 2 D of accommodation in our two monkeys is 4.68 D/s. The maximum accommodative step tested by Hung and Ciuffreda (1988) was 2 D and the maximum step by Campbell and Westheimer (1960) was not more than 3 D. It is of interest that although the maximum human accommodative amplitude is considerably lower than that of rhesus monkeys, for absolute amplitudes, the rate is higher in humans. This may reflect methodological differences, species differences or differences due to voluntary accommodation in humans versus EW stimulated accommodation in anesthetized monkeys. Alternatively, the higher rates of accommodation in humans may be a trade off for lower accommodative amplitudes or simply be faster accommodation. It is also possible, however that the rate of accommodation for 2 D in humans (10 D/s) which represents about 20% of the full accommodative response should be compared against the rate for 20% of the full accommodative amplitude of monkeys, i.e., about 4 D, which interestingly also has a rate of about 10 D/s.

A striking result of this study is that maximum rate of accommodation and disaccommodation increase linearly with increasing amplitude over the full accommodative range. A linear relationship between firing rate of EW neurons and amplitude of accomodation has been shown from single unit recordings in alert rhesus monkeys (Gamlin, Zhang, Clendarid, & Mays, 1994). In behavioral terms this implies that the frequency of firing speed of the accommodative response is dictated by target distance or vergence. Hung and Ciuffreda (1988) showed that rate of accommodation was linearly correlated with accommodative amplitude in humans albeit only to a maximum of 2 D and Schaeffel et al. (1993) suggest that speed of accommodation increases linearly with target distance. This relationship may not have been as evident in prior human studies as we found here in monkeys due to the relatively low human accommodative amplitudes tested and the limited dynamic range of the optometers employed (Tucker & Charman, 1979; Schnider, Ciuffreda, Cooper, & Kruger, 1984; Schor, Lott, Pope, & Graham, 1999).

In monkeys we find that the maximum rate of disaccommodation is linearly related to maximum rate of accommodation and the maximum rate of disaccommodation is higher than the maximum rate of accommodation. Croft et al. (1998) measured dynamic movements of the lens and the ciliary body as millimeter changes from baseline using EW stimulation in rhesus monkeys and show that the movements for disaccommodation are faster than for accommodation. Schaeffel et al. (1993) have also shown with photorefraction in humans that disaccommodation and accommodation are linearly related and also that in most cases disaccommodation is faster than accommodation but the difference in the rates was not as great as the difference observed in this study in monkeys.

A possible explanation for the disparity in rates of accommodation and disaccommodation between humans and monkeys is that EW stimulated accommodation in anesthetized monkeys is accommodation without any visual feedback, i.e., open loop accommodation. Therefore accommodation and disaccommodation in this situation are purely mechanical. However behaviorally there is a constant visual feedback to clear blur for both accommodation and disaccommodation. In anesthetized monkeys, when the stimulus to accommodate is terminated, rate of disaccommodation is likely dictated purely by the mechanical forces that disaccommodate the lens in the absence of any remaining parasympathetic activity. Since no visual feedback is involved, the parasympathetic tonus is completely removed and disaccommodation may occur as fast as is mechanically possible. In conscious humans, however, disaccommodation may be influenced by mechanical forces in combination with some remaining parasympathetic and sympathetic activity which may not allow disaccommodation to reach the maximum velocity that the mechanical components alone could achieve.

Beers and van der Heijde (1994), from measurements of lens thickness showed that the time constants of accommodation are greater than time constants of disaccommodation for all the stimulus amplitudes. It seems reasonable that disaccommodation is faster since it is an active process whereby the extralenticular components such as the posterior zonules and choroid actively pull the ciliary body and the anterior zonules and hence the lens into an unaccommodated form. Accommodation, however relies on a more passive process where the lens is released from the elastic pull of the zonules and the lens capsule moulds the lens against the damping action of lens substance (Beers & van der Heijde, 1994; Koretz & Handelman, 1982). The results reported here suggest that for young monkeys ciliary muscle movement rather than lens viscosity limits rate of accommodation. That accommodative rate is faster at higher stimulus amplitudes suggests that the maximum rate of accommodation is achieved when more EW neurons are recruited, more neurotransmitter released at the ciliary neuromuscular junction, causing a stronger ciliary muscle contraction to better overcome elastic forces of the posterior choroid and zonular fibers to move the ciliary muscle faster. It might be anticipated that at some rate of accommodation, lens viscosity would become a limiting factor, but since no asymptote in rate of accommodation is reached, this does not appear to occur over the full range of accommodative amplitudes available to these two young monkeys. A comparison of rates of accommodation and disaccommodation for monkeys of increasing age may have important implications for understanding the relationship between lenticular and extralenticular factors in the progression of presbyopia.

5. Conclusions

We have used IR photorefraction to study the dynamics of accommodation covering the full range of EW stimulated amplitudes in two rhesus monkeys. Maximum rates of accommodation and disaccommodation increase linearly with amplitude and show no saturation at higher accommodative amplitudes. Maximum rate of disaccommodation is greater than maximum rate of accommodation and the two are linearly related over the full range of accommodative amplitudes. Prior studies comparing rates of accommodation and disaccommodation as a function of age often compare rates for lower accommodative amplitudes of older subjects with rates for higher amplitudes of younger subjects. The results presented here suggest that if rates of accommodation or disaccommodation are to be compared for subjects of different ages, they must consider rates for the same accommodative amplitudes. Understanding accommodative dynamics and how they change with age may provide important insights into understanding some of the changes in the accommodative apparatus that account for the loss of accommodation in presbyopia.

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