# 32

# OBJECTIVE MEASUREMENT OF ACCOMMODATION

*Daniel R. Neal, PhD; Thomas D. Raymond, PhD;
William Trattler, MD; George Beiko, BM, BCh, FRCS, CMD;
Hartmut Vogelsang, Dr rer nat, Dipl-Phys; and Wolfgang Kern, Dipl-Ing (FH)*

As life expectancy increases, so does the number of presbyopic patients seeking a solution to their loss of accommodation and near vision. Numerous approaches have been developed to meet this demand. As discussed in earlier chapters, current methods of providing adequate distance and near vision for the presbyope include spectacles, contact lenses, laser surgery, phakic or pseudophakic IOLs, or corneal inlays. Efforts continue to supplement these essentially fixed-focus corrections with active methods in which the power of the eye or correction is variable, such as the restoration of some natural accommodation or the use of "accommodating" IOLs.

With the availability of many different approaches, all of which claim to satisfy the needs of at least some presbyopes, it has become important to devise improved methods to assess the characteristics of the visual performance that each provides. In the past, it was common to simply measure the distance and near vision, together with the subjective amplitude of accommodation, in the patient before and after the presbyopic correction was introduced and to claim that, if distance vision was maintained and near vision and subjective amplitude apparently improved, the correction was a success. Yet, such measurements gave no real insight into why the visual improvement at near occurred, particularly as to whether the improvement arose from the intended performance of the corrective method or some other cause. This problem becomes particularly acute with those methods that claim to restore a measure of active "accommodation," when any observed improvements in near vision might be due to factors such as reduced pupil diameter, multifocality or other "static" factors rather than a true change in power of the "corrected" eye.[1,2]

It is important then to have objective methods for measuring the range and quality of accommodation after the presbyopic correction has been introduced. Ideally, such methods should not only be capable of assessing the static response/stimulus curve and amplitude of accommodation but should also allow the dynamic characteristics of the accommodation response to be measured. In addition, it would be helpful to assess the extent to which the static characteristics of the corrected eye contribute to performance over a range of distances, a useful starting point being measurements of wave aberration and pupil diameter. These methods should also be easy to apply, as it is desirable that the stability of the visual performance achieved with any presbyopic correction should be regularly monitored to ensure no deterioration occurs.

Pallikaris IG, Plainis S, Charman WN.
*Presbyopia: Origins, Effects, and Treatment* (pp. 267-274).

# MEASUREMENT OF ACCOMMODATION

## Subjective Methods

In the past, the amplitude of accommodation has been measured in several different ways.[3,4] The most common is called the "push-up test" (see Chapter 2).[5] This measures the quality and range of the near vision focus. Because this is strictly a subjective test, it is difficult to separate the various phenomena involved; the measured amplitude inevitably includes the effects of both true changes in ocular power and of depth of focus (DOF). Although a subjective accommodation test allows for the determination of the range of distances over which a given visual acuity is maintained, the pupil size in this configuration is usually unknown, and it is not possible to separate the effects of pseudoaccommodation, DOF, and multifocality from optical accommodation. The test can be viewed as a system-level measurement, or end-to-end result. Because this relies on reports of what the patient actually sees, it is a valuable method for determining overall performance. However, the test often does not measure patient satisfaction, especially for various presbyopic correction schemes that cause some degradation in image quality to provide an increased dioptric range of adequate vision.

## Objective Methods

The first efforts to measure the true changes in ocular power of the eye were made using stigmatoscopy, a partially subjective technique.[6,7] A variety of partially subjective optometers were subsequently used. Changes in ocular power were also inferred from photographic measurements of the form of the crystalline lens. Visual optometers (eg, the Hartinger) were gradually replaced by automated infrared instruments.[2,8-10] Open-view autorefractors, which use a large beam splitter to allow natural viewing of an external target, have proven to be particularly useful. For example, Figure 12-4 in Chapter 12 shows a record obtained with a SRW-5000 autorefractor (Shin-Nippon, Tokyo, Japan) of the dynamic accommodation achieved with a 1CU A-IOL when the stimulus changes sinusoidally over time; note the smaller amplitude (ie, reduced gain) and phase lags present in the response.[10]

More recently, wavefront aberrometers have been preferred for objective accommodative measurement, as these provide substantial additional information about the ocular changes occurring and can provide this information dynamically.

## Wavefront Aberrometer Measurements

A wavefront aberrometer is an excellent tool for making objective accommodation measurement. A number of different technologies are available for measuring the wavefront aberrations of the eye, including dynamic skiascopy, sequential ray-tracing, and Hartmann-Shack wavefront sensing, that have been adapted for accommodation measurement.[11-13] The aberrometer provides a direct measurement of the optical performance of the eye in combination with any correction. The primary measurement is of the wavefront (often described in terms of Zernike polynomials), from which the refraction, spherical equivalent, higher-order root-mean-square (RMS) wavefront aberration, and look angle can be derived. Using these high-resolution instruments, it is also possible to measure the pupil size with some accuracy, and a dynamic series of measurements provides a means for recording the time response of the eye as well.[14] However, different instruments have different limitations on the dynamic and pupil information available. Moreover, a limitation of many instruments is the density of sampling points across the pupil, which may not be sufficient to accurately map wave aberrations that change rapidly or abruptly across the pupil, as is the case with some multifocal contact lenses or IOLs. In addition, most aberrometers using infrared light have problems in dealing with diffractive corrections, which are designed to function at visible wavelengths and to provide both a distance and a near correction across the full pupil.

Most commercial aberrometers have been adapted to the measurement of accommodation. The objective amplitude and steady-state accommodation response/stimulus curve can conveniently be measured using the dynamic stimulation of accommodation (DSA) method[14] in which the patient accommodates to a target presented for a few seconds each at a series of increasing vergence levels. The corresponding accommodation responses are evaluated from the recorded wavefront aberration at each vergence level. Figure 32-1 shows an example of a 44-year-old phakic patient

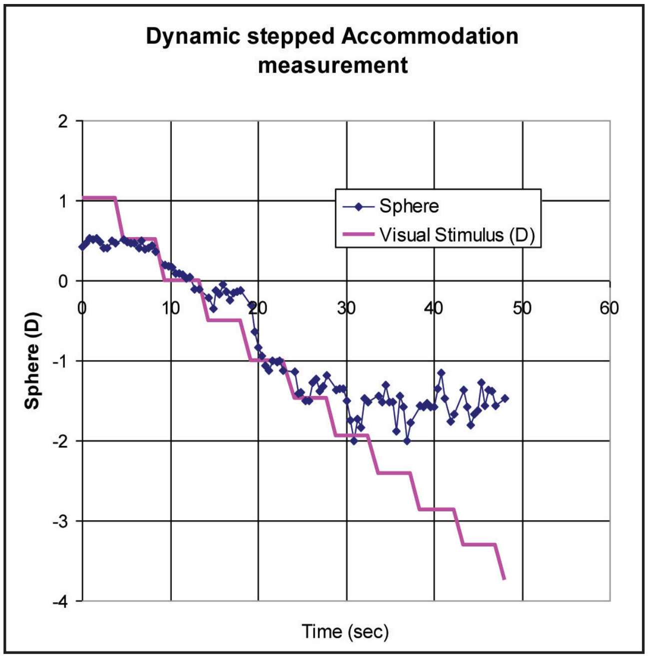

**Figure 32-1.** Dynamic stepped stimulus measure of accommodation. Note that the responses are presented in terms of the ocular refraction, so that increasing negative values represent increases in power of the eye. The 44-year-old patient is mildly hyperopic and has an objective amplitude of approximately 2.00 D.

who was able to track the changing target vergence for 2.00 D until he was no longer able to accommodate, at which point the measured refraction remained constant even as the target presentation was brought closer. Thus, the objective amplitude of accommodation was approximately 2.00 D.

One of the key issues with measuring accommodation is that it is often difficult to know whether the patient has truly fixated and accommodated on the target stimulus. Many patients with normal accommodation fail to accommodate monocularly when presented with the internal fixation/accommodation target used in many aberrometers. To demonstrate this, the measured accommodation range is plotted for a number of normal phakic patients as a function of age in Figure 32-2. The aberrometer used was a Hartmann-Shack instrument, the Complete Ophthalmic Analysis System (COAS; AMO WaveFront Sciences, Albuquerque, NM). In this study, all the patients were carefully trained to keep the internal target in focus as long as possible. No pseudophakic or abnormal eyes were included in the study population, and all patients were familiar with the measurement process. The curve follows the approximate trend of other classic accommodation measurements.[5]

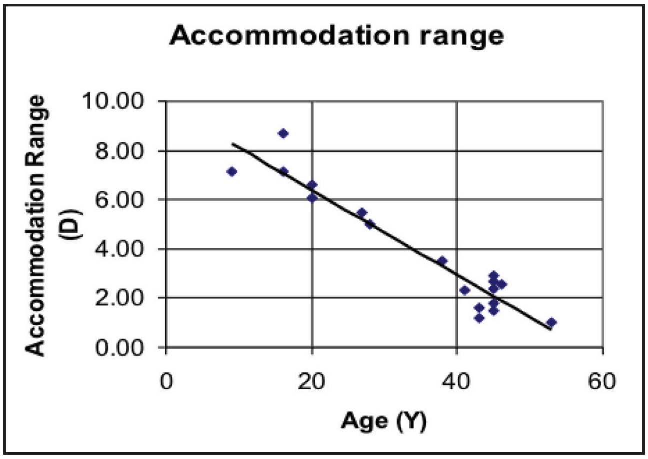

**Figure 32-2.** Measured accommodation range as a function of age using the dynamic stepped target method. This was a small study with individual measurements of 18 eyes to determine methodology feasibility. Each data point is a single measurement.

However, the objective measurements show much less total accommodation at any given age than the classic subjective measurements, largely because the subjective amplitude is increased by ocular DOF.[6,7] In addition, there is a fairly large amount of scatter in the data. Repeated measurements on the same patient showed variations of more than 1.00 D.

Measurements in a clinical setting with a variety of patients have shown that, although some patients focus on the internal target very well, other patients fail to do so, and thus no measurements are possible.

To reduce these problems, it has been found preferable to use an external binocular accommodation target.[15] This provides normal proximity cues and allows more natural accommodation and convergence, thus giving more reliable results. Such a target system is available for the COAS Hartmann-Shack aberrometer (the DSA system) and has been found to usefully reduce fixation problems and provide more reliable measurements.[14]

## DYNAMIC STIMULATION CHANGES

### *Changes in Sphere*

In natural accommodation, when there is an abrupt step change in stimulus, the eye takes some time to readjust its accommodation. First, there is a reaction time or latency of approximately 0.3 to 0.4 sec during which no change occurs. The response then commences and follows an approximately exponential path to be completed in ~0.5 to 1 sec. In practice, the exact response times depend on whether positive or negative accommodation is involved, the size of the stimulus step, the observing conditions, patient age, and other factors (see Chapter 5). Obviously, it is desirable that any presbyopic eye in which accommodation has been "restored" by artificial means should have broadly similar dynamic characteristics; therefore, it is important that these should also be quantitatively assessed. This can be achieved by making aberrometer recordings of the instantaneous refraction at a sufficiently high temporal frequency (eg, 10 Hz).

Figure 32-3 shows the time-dependent pupil and refractive response waveforms for a 30-year-old female phakic patient. These can be quantified in terms of the parameters, such as a "time average" fit (green) or an "exponential" fit (red). The stimulus changes occurred at $t = 4$ and 10 seconds. It is found that the time constant for the exponential fit shows little or no change with age.

## *Changes in Cylinder*

Evidently, it is possible to track the changes in both the spherical and the cylindrical components of refraction as the stimulus is changed. Figure 32-4A shows an example of a 30-year-old man accommodating between 0.00 and -5.75 D stimuli. Note that the change in sphere is approximately 4.00 D, but the cylindrical component remains essentially unchanged.

# CHANGES IN ABERRATIONS

It is also possible to measure (and, if appropriate, to include in the refraction) the changes in higher-order aberrations, as shown in Figure 32-4B. All higher-order aberrations are potentially of interest, as it may be that an A-IOL may change both its tilt and centration when the stimulus is changed, so that aberrations such as coma and astigmatism may change, as well as spherical aberration.

## *Other Temporal Stimuli*

In many studies of normal phakic eyes, other forms of temporal stimulus variation have been used, such as ramp or sinusoidal changes (see Chapter 5). As yet, these have not been widely used in the study of presbyopic eyes in which attempts have been made to somehow restore accommodation.

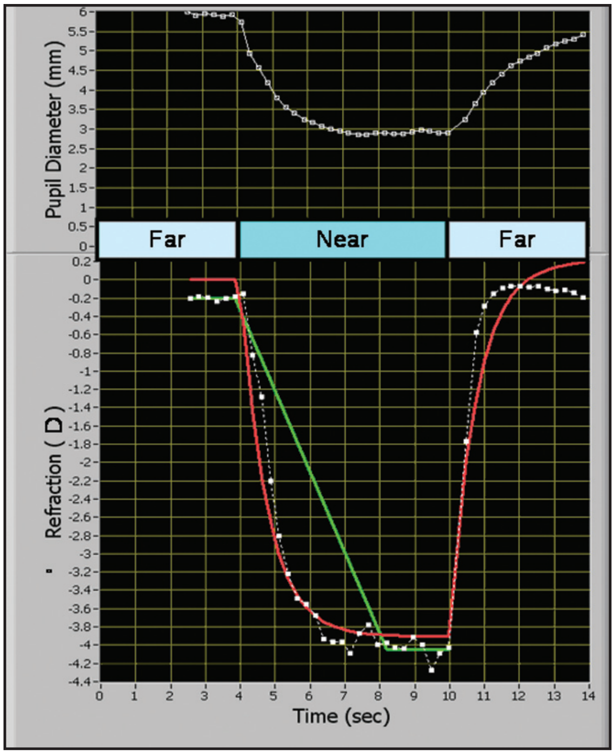

**Figure 32-3.** Step response of the spherical equivalent of a 30-year-old patient. The pupil size is also shown in the top part of the graph. Time average fit (solid green curve) and exponential fit (solid red curve) are shown together with the accommodation measurement (dots).

# CALCULATING THE ACCOMMODATION RESPONSE FROM WAVEFRONT DATA

In most commercial instruments, calculating the accommodation response from wavefront data is carried out automatically, but it will be helpful to consider the procedures involved.

## *Zernike Description of the Wavefront*

As noted earlier, the wavefront surface at any level of accommodation is usually described using Zernike polynomials, although such polynomials may have difficulty in describing aberrations that change abruptly across the pupil.

The wavefront surface is described as a linear combination of these polynomials with coefficients $c_n^m$

$$w(x,y) = \sum_{nm} c_n^m Z_n^m (x,y) \tag{1}$$

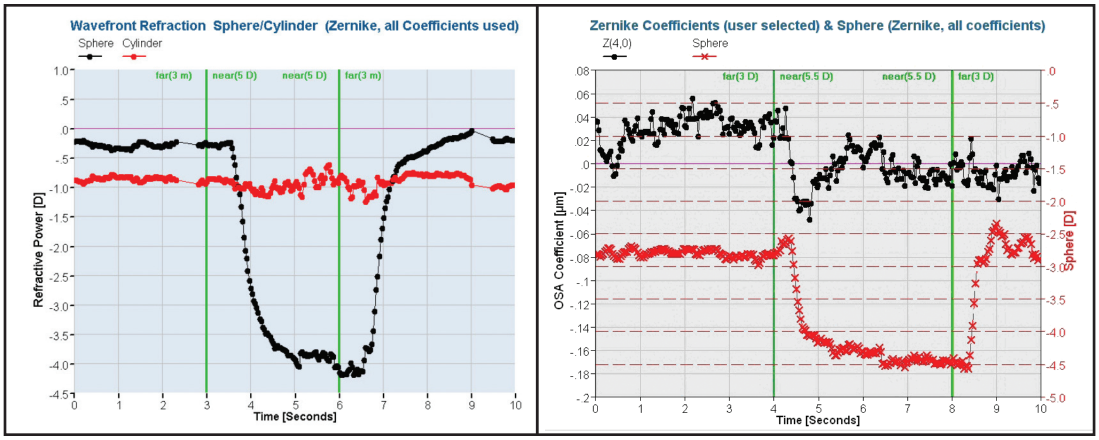

**Figure 32-4.** (Left) Response of a 30-year-old patient to a 5.75-D step stimulus showing temporal changes in sphere (black) and cylinder (red). (Right) Response of a 38-year-old patient to a 5.50-D stimulus showing changes in sphere (red) and Zernike spherical aberration (black).

The fourth-order Zernike expansion of the rotationally symmetric terms of (1) can be written (using the ANSI convention for Zernike polynomials[16]):

(2)

$$W(\rho,\theta) = c_4^0 Z_4^0 + c_2^0 Z_2^0 + c_0^0 Z_0^0$$
$$= c_4^0\sqrt{5}\left(6\rho^4 - 6\rho^2 + 1\right) + c_2^0\sqrt{3}\left(2\rho^2 - 1\right) + c_0^0$$

Noting that, if $r$ is the actual radial distance in a pupil of radius $R$, $\rho = r/R$, so that

(3)

$$W(r,\theta) = c_4^0\sqrt{5}\left(6(r/R)^4 - 6(r/R)^2 + 1\right) + c_2^0\sqrt{3}\left(2(r/R)^2 - 1\right) + c_0^0$$

To calculate the spherical refractive power for any zonal radius $r$ from the rotationally symmetric aberrations ($Z_2^0$, $Z_4^0$, etc), the axial power formula may be used:

(4) $$V = \frac{1}{r}\frac{\partial w}{\partial r}$$

which gives

(5)

$$V = \frac{\partial W(r,\theta)/\partial dr}{r} = \frac{c_4^0\sqrt{5}\left(24r^3/R^4 - 12r/R^2\right) + c_2^0\sqrt{3}\left(4r/R^2\right)}{r}$$
$$= c_4^0\sqrt{5}\left(24r^2/R^4 - 12/R^2\right) + c_2^0\sqrt{3}(4)/R^2$$

As $r$ approaches zero, V approaches the paraxial value

(6) $$V(r \to 0) = \frac{c_2^0 4\sqrt{3} - c_4^0 12\sqrt{5}}{R^2}$$

## Seidel Versus Zernike Refraction

In accommodation studies, only some of the Zernike coefficients are used to calculate the responses. Essentially, each response level is calculated as a refraction. Several methods have been proposed for calculating refraction from the wavefront data.[17,18] Although some of these methods rely on calculation based on image-plane, point-spread function analysis, it is generally simpler to calculate the refraction based on the Zernike representation of the wavefront surface. The vector notation refraction can be calculated as the expansion terms that best fit the spherocylindrical refraction in the center of the pupil. Depending on the order of approximation, these calculations are referred to as Zernike refraction, Seidel refraction, and extended Seidel refraction. They are defined as:

### Zernike Refraction

(7) $$J_{180} = -\frac{2\sqrt{6}C_2^2}{R^2}$$

(8) $$J_{45} = -\frac{2\sqrt{6}C_2^{-2}}{R^2}$$

(9) $$M = -\frac{4\sqrt{3}C_2^0}{R^2}$$

with

(10) $$C = -2\sqrt{J_{180}^2 + J_{45}^2}$$

and

(11) $$S = M - C/2$$

## Seidel Refraction

One common way to take note of the higher Zernike polynomial orders is to include some of these terms in calculation of the components of the refraction, such as we can include fourth-order spherical aberration when calculating *M* by using the equation:

$$(12)\quad M = -\,[\,4\sqrt{3}C_2^0 - 12\sqrt{5}C_4^0\,]\,/\,R^2$$

Note that this is equation 6 with signs reversed, as *M* is a correction of the wavefront's power.

## Extended Seidel Refraction

When more terms are included, such as up to the tenth order, the "astigmatic components" → $J_{180}$, $J_{45}$ are also affected:

(13)

$$M = -\,[\,4\sqrt{3}C_2^0 - 12\sqrt{5}C_4^0 + 24\sqrt{7}C_6^0 - 40\sqrt{9}C_8^0 + 60\sqrt{11}C_{10}^0\,]\,/\,R^2$$

(14)

$$J_{180} = [\,2\sqrt{6}C_2^2 - 6\sqrt{10}C_4^2 + 12\sqrt{14}C_6^2 - 20\sqrt{18}C_8^2 + 30\sqrt{2}C_{10}^2\,]\,/\,R^2$$

(15)

$$J_{45} = [\,2\sqrt{6}C_2^{-2} - 6\sqrt{10}C_4^{-2} + 12\sqrt{14}C_6^{-2} - 20\sqrt{18}C_8^{-2} + 30\sqrt{2}C_{10}^{-2}\,]\,/\,R^2$$

The primary difference between the Zernike refraction and the Seidel refraction is that the spherical aberration term is taken into account in one (Seidel refraction) and not in the other (Zernike refraction). This can significantly affect the response values obtained. Consider Figure 32-5, which is a dynamic measurement of a single accommodative response of a 20-year-old man to successive far-to-near and near-to-far 9.00-D step stimuli. Both the sphere refraction value and the $C_4^0$ spherical aberration coefficient are plotted as a function of time. The figure on the top shows the Zernike refraction (without inclusion of the spherical aberration terms), whereas the figure on the bottom shows the extended Seidel refraction with the spherical aberration included (Eq. 13). Note that the $C_4^0$ term has different time dependence from the sphere term, and thus affects the overall refraction calculation. Generally, it has been shown that the Seidel method more closely matches manifest refraction.

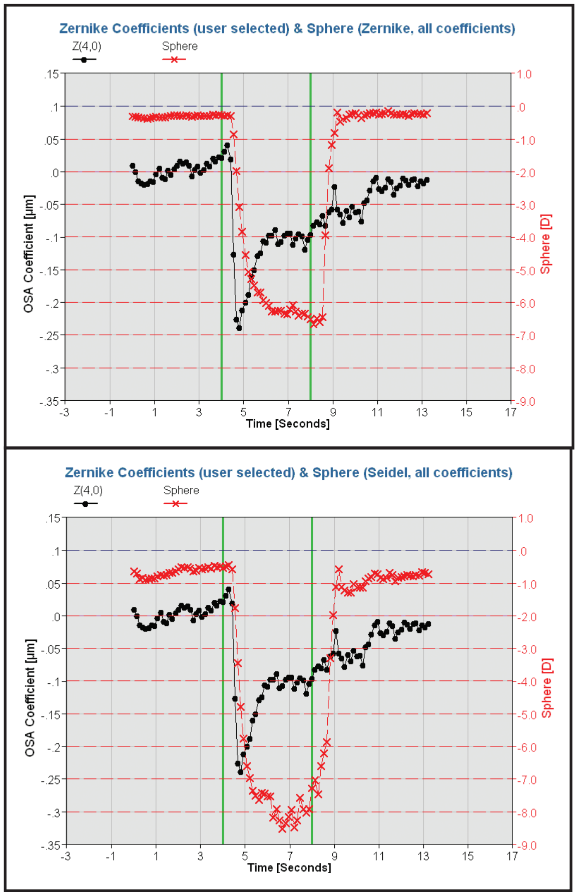

**Figure 32-5.** Example of the response of a 20-year-old patient to a 9.00-D step stimulus. The 2 panels show the same response. In both panels, the black curve gives the Zernike $C_4^0$ spherical aberration coefficient with values shown by the left-hand ordinate scales. The red traces and right-hand ordinate scales show (top) Zernike refraction and (bottom) extended Seidel refraction. Note the marked differences in the absolute values of the accommodative response as assessed using the 2 estimates of refraction.

# EFFECTS OF AGE

The time-dependent accommodation step responses of some representative phakic patients of different ages are shown in Figure 32-6. Clearly, the amplitude of the accommodative change diminishes with age, although the time taken to initiate and complete the response is almost constant with age.

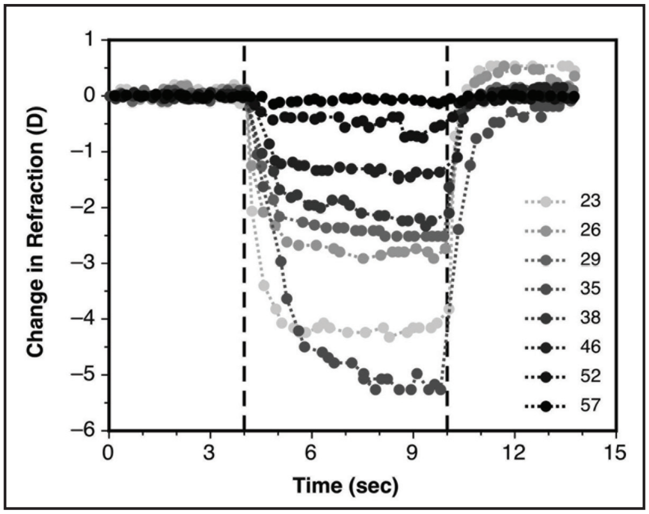

**Figure 32-6.** Temporal characteristics of step responses in patients of different ages.

## SUMMARY

Several methods are currently available for the objective evaluation of accommodation in both phakic and pseudophakic eyes. Repetition of such tests at intervals of time is desirable to allow the continuing effectiveness of any presbyopic correction to be monitored, as any initial accommodation may not be sustained due to such factors as capsular fibrosis. Dynamic aberrometry is a particularly effective method and can be used to assess the steady-state response/stimulus curve and to determine the objective amplitude of accommodation of either phakic or pseudophakic patients. It also provides dynamic measurements, such as the step response time-dependence. The wavefront aberrations and pupil size are also measured as a function of time, allowing the various factors contributing to the observed subjective amplitude of accommodation to be more fully explored.

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