Rapid objective refraction using evoked brain potentials

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With no prior information of either spherical or cylindrical components, objective (evoked potential) refraction can be performed up to 100 times faster than by comparable averaging procedures. The new procedure is to directly obtain the required graph of evoked potential (EP) amplitude vs. some stimulus parameter rather than to make separate measurements of each point on the graph. Fourier-analyzed EP's provide the clinician with an immediate indication of the result of altering refractive correction, so that this EP procedure is analogous to conventional subjective refraction. While the subject views the pattern through a rotating stenopeic slit, a 10-second plot of EP amplitude vs. slit angle can indicate the axes of astigmatism to within 10°. The slit is then set parallel first to one axis of astigmatism and is then turned through 90° while the subject views the pattern through a lens whose power is continuously oscillated. Each of these two graphs of EP amplitude vs. lens power can be obtained in 10 to 20 seconds; these data give a complete description of the required refractive correction to within 0.5 D. The use of checks rather than stripes gives a faster procedure.

Key words: objective refraction, evoked potential refraction, visual acuity, pattern evoked potentials, astigmatism.

When the eye is visually stimulated, the human brain generates electric currents. These brain responses can be recorded as changes of the electric voltage between electrodes attached to the scalp, and are called evoked potentials (EP's). Evoked potentials elicited by spatially patterned visual stimuli have been shown to be sensitively influenced by the sharpness of focus of the retinal image. Provided that certain requirements are met, the sharpest retinal image gives the largest EP, so that EP recording offers a means for objective refraction.

Millodot and Riggs pointed out that, in principle, EP refraction is capable of providing surer indications that refraction is optimal than the classical objective methods of retinoscopy and refractometry. This is because EP's depend on the same initial physiologic processes as visual perception. Nevertheless, EP refraction is still almost entirely a laboratory technique. Perhaps the major insufficiency which hinders its wider acceptance in clinical practice is the lengthiness of the procedure. This article de-
Fig. 1. Apparatus for visual stimulation and evoked potential analysis. A. P = projector; S = light source; L = lenses; T = patterned transparency vibrating f/4 times per second; V = vibrator and circuit to convert sinewave to square wave input; Sc = screen; RS = rotating stenopeic slit; A = EEG amplifier; M1, M2 = multipliers; RSS = device which computes \( \sqrt{a^2 + b^2} \), the square root of the sum of the squares of the multipliers' outputs, where \( \sqrt{a^2 + b^2} \) is proportional to EP amplitude. B. Arrangement for presenting polar display of EP amplitude vs. angle of stenopeic slit. Signal proportional to EP amplitude (\( \sqrt{a^2 + b^2} \)) fed from RSS to multipliers M3 and M4; \( f = 2 \) the stenopeic slit's rotation frequency; D = X-Y oscilloscope or X-Y plotter. C. Generation of sine and cosine signals locked to rotation of stenopeic slit RS or to oscillations of dioptric power of variable-power lens (VPL); R = rotating device that generates sine and cosine waves; M = motor that drives R and RS or R and VPL through gears.

Describes EP refraction using a method that is much faster than previous methods. The increase in speed can amount to a factor of more than 100 times over comparable averaging procedures. The method is designed to handle both astigmatic and spherical errors in refraction.

Methods

Stimulation. The subject viewed a pattern of bars or checks projected onto a screen (Fig. 1). The screen was located sufficiently far from the subject's eye (15 ft.) to avoid effects of working distance. The pattern was a transparency mounted on a vibrator which moved abruptly to and fro through the width of one bar or check. The bright and dim parts of the pattern thus appeared to repetitively exchange places \( f \) times per second. Such pattern-reversal stimulation has the advantage that it does not involve any change of total light flux. The bright and dim parts of the pattern thus appeared to repetitively exchange places \( f \) times per second. Such pattern-reversal stimulation has the advantage that it does not involve any change of total light flux.  

Spekreijse and Cobb, Morton, and Ettlinger reported that pattern-reversal EP's were attenuated by blurring the retinal image. On the other hand, the situation is not always so straightforward. When check size exceeds 25 to 35 minutes, EP amplitude may increase when the retinal image is blurred. This potential ambiguity was avoided by using checks and bars of 20 minutes' subtense or smaller.

The contrast difference between bright and dim checks or bars was restricted to below 30 per cent in order to avoid complications due to EP saturation. Contrast was set by diffusely illuminating the screen by means of a second projector (not shown in Fig. 1A). The mean stimulus luminance was 1.5 log ft. lambert (110 cd. per square meter).

A large stimulus field of 7° diameter was chosen in order to minimize EP changes caused by minor alterations in the direction of gaze. In order to restrict demands on patient's cooperation, focal retinal stimulation was not attempted, and the center of the 7° stimulus was fixated. On the face of it, central fixation is undesirable, since EP's due to stimulation of upper and lower retinal half-fields may cancel to a greater or lesser extent. For the present practical purpose this problem was...
minimized by referentially recording from an electrode on the inion (left mastoid reference). Of a total of 8 subjects studied, three of whom required refractive correction, all gave large EP's at the inion, and in all except one case these EP's were predominantly determined by stimulation of the lower visual half-field.

In some experiments the subject looked at the stimulus pattern through a 1 by 5 mm. stenopeic slit located immediately in front of his cornea (RS in Fig. 1A). Fig 1C shows a front view of the rotating stenopeic slit (RS).

In an alternative version of Fig. 1C, RS could be replaced by a rotating Dove prism located immediately in front of the stimulus projector's light source, and a slit image of the source some 1 mm. wide imaged onto the subject's cornea. Rotating the Dove prism would rotate the orientation of the slit image and thus produce the same effect as rotating the stenopeic slit, but without the unpleasantness of having a rotating slit near the eye.

In other experiments, RS was replaced by a variable-power lens whose power was oscillated \( f/2 \) times per second. Two variable-power optical devices were used. One comprised a rotating cylindrical lens of K diopters placed immediately behind a narrow slit. Thus the effective power of this device oscillated between 0 and K diopters. The second device comprised a fixed negative lens placed immediately before the eye combined with a second positive lens whose distance from the negative lens was repetitively varied.

Evoked potential analysis. A price must be paid for increasing the speed of EP analysis. The theoretical basis for speed difference between the averaging method and the method described here is that quantity of information was traded for speed. However, speed is valuable in the clinical situation, whereas the price paid (i.e., information thrown away) is of comparatively little importance in refraction.

Repetitive stimulation has the result that stimulus information is effectively restricted to a few very narrow frequency bands.\(^{15, 16, 22, 23}\) For the purpose of EP refraction it is sufficient to record EP components restricted to a narrow frequency band centered on \( f \) Hz. where the stimulus executes \( f \) pattern-reversals per second.\(^{14}\) An important point is that the value of \( f \) may be chosen to avoid frequencies where electroencephalogram (EEG) noise is high (e.g., the alpha region).

This point is illustrated in Reference 15 Fig. 5.12. The value of \( f \) was chosen as 6 to 7 Hz. in the present experiments not only because this avoids the alpha activity near 10 Hz., but also because EP's are conveniently large at 6 to 7 Hz.\(^{16}\) Furthermore, since stimulus phase (latency) is unimportant here\(^{16}\) it can be rejected leaving the amplitude of the \( f \) Hz. EP component as the sole information recorded. The investigator can therefore trade bandwidth for speed.

The \( f \) Hz. EP component was recorded by separately multiplying the EEG by sine and cosine waves of frequency \( f \) Hz. (Fig. 1A)\(^{22, 23}\) The two products of multiplication (a and b) were then fed to a device whose output gave the instantaneous value of

\[
\sqrt{a^2 + b^2}
\]

which was therefore proportional to the instantaneous value of EP amplitude.\(^{15, 22, 23}\) After low-pass filtering, this signal was fed to both a pen recorder and to the device shown in Fig. 1B. The pen recorder gave a plot of EP amplitude vs. time in Cartesian coordinates. On the other hand, the device of Fig. 1B displayed a plot in polar coordinates of EP amplitude vs. the angle of the stenopeic slit. The polar plot was arranged in the following way.

Motor M in Fig. 1C drove resolver \( R \) and stenopeic slit \( S. \) through gears so that the slit rotated \( f/2 \) times per second, and \( R \) generated sine and cosine signals of frequency \( f \) Hz. Fig. 1B shows how the EP signal was separately multiplied by this sine and by this cosine. These two products of multiplication were displayed either on an X-Y plotter or on a CRO in X-Y mode. In this X-Y display the distance of any point from the origin represented EP amplitude, while the direction to the point from the origin indicated the orientation of the slit. A necessary condition here was the \( f \) was much less than \( f \). In the present experiments \( f \) and \( f \) were never closer than, respectively, 0.1 Hz. and 6 Hz.

Results

Determination of spherical approximation to refractive correction. The spherical approximation could be obtained rapidly by finding the trial lens which gave the largest EP. This was done by systematically inserting and removing trial lenses while looking at a running-average display of EP amplitude. In Fig. 1 the instantaneous value of EP amplitude was given by the output of RSS displayed as a pen recording or as a pointer indication. A technically simple and cheap alternative was to replace RSS by an oscilloscope in X-Y mode with a

\(^{15}\)For the purpose of EP refraction a considerable technical simplification is possible here. Since third harmonic EP components to pattern are negligible,\(^{15}\) the reference waves for multiplication can be quadrature squarewaves rather than quadrature sine-waves. Multiplication by squarewaves is equivalent to simply switching the EEG on and off (e.g., by a relay or FET). Furthermore, quadrature squarewaves of variable frequency may be generated more straightforwardly than quadrature sine-waves (e.g., by a ring counter).
Fig. 2. Astigmatism shown by evoked potentials elicited by a pattern of stripes. A. Static method: stripe orientation constant during the recording of any point on the graph. Dashed line = astigmatism uncorrected, but -2.5 D. sphere in front of eye. EP amplitude peaks when stripes orientated at approximately 130°. Continuous line = astigmatism corrected by prescription lens. Noise level shown by horizontal dotted line (light occluded). B, C, and D. Rotating-stripe method: orientation of stripes continuously rotated through 180° every 30 secs. B. Noise level, stimulus pattern occluded. C. Astigmatism uncorrected, viewing through -2.5 D. sphere. EP amplitude peaked when stripe orientation was approximately 130°. D. Astigmatism corrected by prescription lens. EP amplitude now much less affected by stripe orientation than in C. Bar width 10 minutes. Accommodation not paralyzed. Fig. 4H gives key to angular measures of orientation.

The running-average presentation and a brief suggestion of its possible use for on-line assessment of spherical approximation have been reported previously.

In this application the apparatus may be simplified by replacing multipliers M1 and M2 by switches (see above). A faster but more complex development is to replace trial lenses by a lens of continuously variable spherical power (see below).
**Determination of the axis of astigmatism using a stripe pattern.**

**Nonrotating stripes.** Fig. 2A (dashed line) shows that EP amplitude was maximal when the angle of the stimulus stripes was near 130°. This was also the angle at which the subject set the stripes when adjusting for maximum image sharpness. The physical orientation of the stripes when they were set at an angle near 130° is illustrated in Fig. 4H. The angle of the stripes that gave the largest EP could be read off Fig. 2A to within roughly ± 10° in accord with previous reports. The continuous line in Fig. 2A shows the effect on EP amplitude of varying the orientation of the stripes after the eye’s astigmatism had been corrected. By comparing the dashed and continuous lines in Fig. 2A it can clearly be seen how this EP method indicates both (1) the axes of astigmatism and (2) when astigmatism has been corrected.

However, even though the recordings of Fig. 2A were made by on-line Fourier analysis rather than by the slower averaging method,

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**Rotating stripes.** Figs. 2B, C, and D illustrate a development of the procedure of Fig. 2A. This development enables the graph of Fig. 2A to be obtained much more rapidly. In Figs. 2B, C, and D the dark and bright stripes exchanged places 6 times per second, exactly as in Fig. 2A. However, the stripes did not remain at a fixed orientation while each separate recording was made. Instead the stripes continuously changed their orientation, rotating from an angle of 0° through 180° in 30 seconds. Fig. 4H illustrates one rotation. A pen recorder gave a running display of EP amplitude vs. time. This display is also calibrated as EP amplitude vs. stripe angle in Figs. 2B, C, and D. Fig. 2B shows a control experiment in which the stripe pattern was occluded, but the rest of the equipment continued to run. The trace of Fig. 2B can be regarded as a noise level. In Fig. 2C the subject viewed the continuously rotating stripe pattern. EP amplitude rose and fell markedly as the angle of the stripes changed progressively. Fig. 2C shows that maximum EP amplitude was recorded when the stripes were at an angle of 130°, in agreement with Fig. 2A. Fig. 2C was recorded after astigmatism had been corrected, and showed that the peak and trough of Fig. 2C was now absent.

Fig. 2A gives the same clinical information as Fig. 2C plus 2D. However, Figs. 2C and D are untouched records of the pen traces obtained during two 30-second experiments, whereas roughly 30 to 40 minutes were required to record, compute, and plot the curves of Fig. 2A.

**Determination of the axes of astigmatism using a stenopeic slit.**

**Stationary slit.** A stenopeic slit enabled the axes of astigmatism to be determined by recording checkerboard EP’s rather than stripe EP’s. The EP’s of Fig. 3 were recorded when a slit 1 mm. wide by 5 mm. long was placed immediately in front of the subject’s cornea. Fig. 3A is a plot of EP amplitude vs. slit orientation in degrees. The physical meaning of the angles marked on the graph are illustrated in Fig. 4H. Fig. 3A shows that EP amplitude was strongly affected by slit orientation. The largest EP’s were recorded for a slit angle of 45°, and at this point the subject reported that the check pattern appeared sharpest. A slit angle of approximately 140° gave the smallest EP. The slit angle which gave the largest EP could be read off Fig. 3A to an accuracy of roughly ±10°.

**Rotating slit.** Fig. 3B shows a development of the stenopeic slit method that is much faster than the method of Fig. 3A. The two untouched pen recordings of Fig. 3B each give as much information as Fig. 3A, although each was obtained in 18 seconds in contrast to the (roughly) 20 to 30 minutes required to record, compute, and plot Fig. 3A.
Fig. 3. Axes of astigmatism shown by evoked potentials elicited by a pattern of checks viewed through a stenopeic slit. A. Static method: orientation of stenopeic slit constant during the recording of any point on the graph. EP amplitude peaked when slit orientation was 45°. B, C, and D. Rotating-slit method: B. Orientation of slit continuously rotated. EP amplitude peaked when slit orientation was 45°. Two plots shown, each obtained in 18 seconds. C. Control recording with slit replaced by circular aperture. D. Continuous recording taken during 4 successive rotations of slit to illustrate consistent indication of 45° axis of astigmatism. Subject viewed through −2.5 D. sphere. 20 minute checks. Accommodation not paralyzed.

In Fig. 3B the stenopeic slit was not stationary as in Fig. 3A, but rotated continuously. The slit rotated through 180° in 18 seconds. A pen recorder gave a running display of EP amplitude vs. time. Two such recordings are shown in Fig. 3B where the horizontal (time) axis has been marked in terms of slit angle. Two separate recordings are shown to illustrate consistency. In both records EP amplitude was maximal at a slit angle of approximately 45° in agreement with the stationary slit results of Fig. 3A.

Fig. 3C shows a "noise" control recording for which the slit was replaced by a circular aperture although otherwise the apparatus was as for Fig. 3B.

In Fig. 3D the slit was replaced and recordings made to show variability during several successive slit rotations. Each suc-
Fig. 4. Axes of astigmatism displayed by polar plot of EP's elicited when a pattern of checks was viewed through a rotating stenopeic slit. A, B, and C. Three replications of EP's recorded while the stenopeic slit rotated through 180° in 18 seconds. The instantaneous value of EP amplitude was given by the length of the line joining the origin of the axes to any given point on the trace, and the corresponding slit orientation was given by the orientation of this line. Thus EP amplitude is largest in the upper left quadrants of A, B, and C, and this corresponds to a slit angle of 30° to 50° as shown in G. The slit orientation corresponding to 30° to 50° is shown in H. Similarly A, B, and C show that minimum EP magnitude was recorded for slit angles of 110° to 140°. D. EP's recorded during one slit rotation after astigmatism had been corrected. E. Similar to A, B, and C, but recorded in 10 seconds. F. Five microvolt calibration. Accommodation not paralyzed.

Rotating slit stimulation; polar display. The polar display of data in Fig. 4 was intended to assist the experimenter to both rapidly detect astigmatism and to assess the axes of astigmatism.

The plots of Figs. 4A, B, and C present similar data to that shown in Figs. 3B or 3D. The difference is that Fig. 3 shows plots of EP amplitude vs. slit angle in Cartesian coordinates, whereas in Fig. 4 these data were automatically displayed in polar coordinates. Fig. 4G shows the direction of radii which corresponds to the slit angles illustrated in Fig. 4H. The distance along a given radius is proportional to EP amplitude in the EP plots of Fig. 4.

Fig. 4A shows visually that EP amplitude was very small when the slit angle was at 110° to 140° whereas EP amplitude was largest between slit angles of 30° to 50°. This was confirmed by the replications Figs. 4B and 4C, which also indicates variability. The polar display of EP data gives an immediate and direct indication of the slit angles for which EP amplitude is largest and smallest (i.e., the axes of astigmatism). Traces such as those of Figs. 4A, B, and C can conveniently be displayed as a single rotation of a cathode ray oscilloscope's spot.

Fig. 4D was recorded after correcting...
Fig. 5. Determination of lens prescription for optimal correction of refractive errors. A. Static method. Lens power constant during the recording of each point on the graph. Plot shows EP amplitude vs. the power of the trial lens. The subject viewed a checkerboard pattern first through a stenopeic slit set parallel to one axis of astigmatism, then with slit orientation rotated through 90°. Dotted lines show noise levels. B. Illustrates dynamic method and its analogy with routine subjective refraction. On left a -2 D. trial lens was abruptly added and then removed so as to change the total correction from -2.5 D. to -4.5 D. and back again. EP amplitude rose immediately when the lens was added, and immediately fell when the lens was removed. On the right side the EP immediately shows that the addition of a further -2 D. lens (so as to raise total correction from 4.5 D. to -6.5 D.) now degraded refractive correction. Accommodation was paralyzed with 1 per cent Mydriacil.

for astigmatism. For no slit direction was EP amplitude greatly larger or smaller than the mean, in contrast with precorrection recordings of Figs. 4A, B, and C.

Fig. 4E was obtained in 10 seconds and can be seen to be essentially similar to the 18-second records of Figs. 4A, B, and C. Fig. 4F is a 5 microvolt calibration.

Measurement of lens power for refractive correction by using trial lenses.

Static method. The subject looked at a checkerboard stimulus through a stenopeic slit aligned along one axis of astigmatism. Lenses of different powers were then successively placed before his eye and a separate EP recorded for each lens power. Fig. 5A shows that along one axis EP amplitude was a maximum for a -2.5 D. lens, whereas a -4.5 D. lens gave the largest EP's when the slit was set parallel to the other axis. These two lens powers can be read off Fig. 5A to within roughly ±0.5 D. These two values of orthogonal refractive correction fully define the required prescription lens.

Dynamic method. Fig. 5B shows the effect of abruptly increasing or decreasing lens power. The stationary stenopeic slit was set at an angle which required a correcting lens of -4.5 D. for optimal refraction (Fig. 5A). The left side of Fig. 5B shows that abruptly adding a -2 D. lens to the -2.5 D. lens already in place caused an immediate increase of EP amplitude, whereas removing the -2.5 D. lens produced an immediate drop of EP amplitude. The arrows in the figure show where the lens was inserted and removed.

Optimal refraction was now obtained by placing a -4.5 D. lens before the eye. The right side of Fig. 5B shows how abruptly inserting a further -2 D. lens now caused EP amplitude to immediately fall, whereas removing this extra lens produced an immediate rise of EP amplitude.

By reference to Fig. 5A it is easy to understand these contrasting effects of inserting a -2 D. lens so as to change total correction (1) from -2.5 D. to -4.5 D., and (2) from -4.5 D. to -6.5 D.
Measurement of lens power for refractive correction by using lens of oscillating power. The stenopeic slit method of Fig. 5 was greatly speeded by using a lens of continuously variable power rather than a set of fixed-power trial lenses.

The upper and lower halves of Fig. 6 show EP's recorded when the slit was set parallel to the two axes of astigmatism. The subject looked at the checkerboard pattern through the slit. The power of the lens was oscillated between predetermined limits (here -2 D. and -4.5 D.) at a rate of one cycle in 18 seconds. Both time and instantaneous lens power are plotted along the abscissae of Fig. 6.

Fig. 6 can be directly compared with Fig. 5A. Either gives sufficient information to define both astigmatic and spherical refractive correction. However, each trace in Fig. 6 was recorded in 18 seconds, whereas roughly 30 to 40 minutes was required to record, compute, and plot each graph of Fig. 5A.

Discussion

Although the Fourier analysis method of recording steady-state EP's elicited by repetitive stimulation has been in use for more than 10 years, the technique has not been widely used and may be unfamiliar. Nevertheless, in some circumstances Fourier analysis has marked advantages over the well-known averaging method. For example Fourier analysis may be both more sensitive and very much faster in some clinical situations where these features are valuable. This article presents several methods of objective (EP) refraction using Fourier analysis that can be carried out in a much shorter time than comparable averaging procedures. The preferred method for clinical work uses a rotating stenopeic slit, and allows the EP refraction procedure to be speeded by more than 100 times. This method does not require any prior information of either spherical or cylindrical components.

Fourier analysis can give an on-line display of instantaneous EP amplitude. One advantage of this (as illustrated in Fig. 5B) is that EP amplitude can then be treated as equivalent to a patient's verbal responses in conventional subjective testing. An immediate rise of EP amplitude is equivalent to the statement "that lens change makes the pattern sharper" while an immediate fall of EP amplitude means, "that lens change makes the pattern more blurred." The salient point here is that there is no need to wait for the EP reading
to settle down, since the immediate direction of change conveys all the information required. For this reason there is some advantage in differentiating the EP readings of Fig. 5B so that the polarity of an electrical pulse indicates whether the lens change improves or degrades the refractive correction.

The preferred practical refraction procedure is as follows: (1) Use the rotating-slit method to find the axes of astigmatism; (2) set the slit parallel to one axis of astigmatism and use the oscillating-power lens method to find the optimal lens power; (3) repeat (2) with the slit set parallel to the other axis of astigmatism. This procedure gives three items of information (direction of axis and two lens powers) that together are sufficient to define the prescription lens for refractive correction including both spherical and cylindrical components.

The stenopeic slit method for dealing with astigmatic correction has two main advantages over the use of bar or grating stimulus patterns. The first advantage is that a checkerboard stimulus pattern may be used to assess astigmatic correction. Since checkerboard patterns give appreciably larger EP's than bar or grating patterns (roughly 1.5 to 2 times larger, in accord with previous estimates), signal-to-noise ratios are more favorable, so that EP measurements may be more precise. Alternatively, they may be obtained more quickly (up to 4 times more quickly). The second advantage is that, since rotating the stenopeic slit does not affect the orientation of the stimulus pattern on the retina, the method directly assesses corneal astigmatism and does not confound this with any orientation differences in contrast sensitivity or acuity present in both fully corrected astigmats (meridional amblyopia) and in normal subjects. The stripe method, on the other hand, is likely to confound refractive astigmatism with both meridional amblyopia and other orientational differences, since astigmatism is assessed by varying the orientation of the stripes’ retinal images (for example, Fig. 2A shows a residual variation of EP amplitude with stripe angle in the corrected eye). This confusion may hinder the interpretation of EP recordings since, although refraction can correct astigmatism caused by toroidal corneal curvature, refraction does not correct that part of astigmatic defect due to meridional amblyopia.

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