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COMPUTER – ASSISTED EYE EXAMINATION

II. VISUAL EVOKED RESPONSE MERIDIONAL REFRACTOMETRY*

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ABSTRACT

A visual evoked response (VER) or visual evoked potential (VEP) method was studied in order to test its feasibility for objective refraction. An alternating bar grating generated the VER which would directly include the measurement of astigmatism. It was discovered that latency as well as amplitude of the evoked response were affected by the image clarity. Sensitivity to focus was estimated to be ± 1 diopter with the amplitude criterion. The latency criterion appeared to be promising for quantitative analysis of blur. Comparison of our results were made with those of others, and differences discussed. It appears that the VER is not as sensitive to optical degradation of bar gratings as to checkerboards. Suggestions are made for improvement of the methods in order to obtain better sensitivity to focus changes.

From the early days of eye refraction up to the present, the full attention of the doctor has often been required in order to arrive at the best solution for a patient's visual problems. Much of the time required of the doctor, however, has not necessarily been consumed in tasks which require the use of his highest levels of skill and training.¹ This situation did not present a serious problem when the supply of visual care could meet the demand by the general public. Today that situation appears to be changing, and methods are being devised to relieve the doctor of those duties which do not require his attention, thus leaving more time for those problems which do. One way of doing this is through the use of office assistants of one sort or another. Considering recent advances in computer technology it seems feasible that one such assistant could be a computer²⁻⁵.

The computer can be used in a variety of ways, including the measurement of refractive error by both subjective and objective methods. An objective method can be purely optical by the use of a retinoscope or one of the recently developed objective optometers, or it can be bioelectro-optical by the use of the Visual Evoked Response (VER).

Basically, the VER is a recording, from the scalp, of minute electrical currents arising primarily from the visual cortex during various kinds of visual stimulation. It has been shown by several investigators⁶⁻⁹ that these electrical currents can be modified by the degree of focus of the retinal image. Thus the VER can provide a direct and objective indication of refractive error. The VER could contribute significant information about refractive error especially in those cases where subjective methods cannot be used. Such instances are generally caused by communication breakdowns such as language barriers, poor intelligence, immaturity, and malingering.

Like any ideal refractive method, the VER should perform as follows:

1. It should provide an accurate estimate (± 0.25 D or better sensitivity)

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of refractive error.

2. It should not take an excessive amount of time.
3. It should not cause pain or discomfort.

Fortunately, VER methods cause no pain or discomfort. The accuracy and time specifications cannot be summarily answered without careful consideration. The accuracy of the VER methods are roughly proportional to the amount of time involved, assuming constant attention. In this regard, Duffy and Rengstorff⁶, Ludlam and Meyers⁷, and Millodot and Riggs⁸ have found that quite accurate approximations can be made in a reasonable amount of time with selected patients. Harter and White⁹, who originally systematically investigated the effect of focus on the VER did not explicitly determine its accuracy and speed, although they demonstrated that the VER is quite sensitive to focus.

The VER method we have chosen is basically that used by Millodot and Riggs, except that we have used bar gratings instead of checkerboards in order to isolate the meridional response. In this way we have attempted to find the refractive state of the eye, in conventional clinical formulation, by mathematically combining the VER refraction results in three separate meridians.

METHODS

Ideally, the VER should estimate refractive error without prior knowledge of it. In order to keep recording time to a minimum, and yet obtain an accurate estimate of refractive error, it is helpful to use some method which is not totally "trial and error," especially for the refining of an astigmatic correction. However, as in ordinary clinical practice, time can be saved if a previous estimate of the refractive error can be used as a starting point.

It is possible to calculate the total refractive power of any regular spherocylindrical lens if the power of each of three meridians is known¹⁰. The same principles can be applied to the refractive state of the eye. Brubaker, Reinecke, and Copeland¹¹ and Brubaker, Reinecke, and Newman¹² have developed the methodology and mathematics for such a subjective method and have named it "meridional refractometry." We have developed it as an objective method with the VER. The VER is used to find the refractive state of each of the three meridians. Being able to test just three meridians eliminates most of the "trial and error" of examination which, in principle, decreases examination time. Their equations are shown in Appendix A.

Our computer program for meridional refractometry has been written in 8-K FOCAL (see Appendix B and Fig. 7) for use on a Digital Equipment Corporation PDP-8I computer. (Copies are available on request.) Eventually it can be included within a general sequence for computer-assisted eye examination as a sub routine.

In order to measure refractive error by meridional refractometry, it is simplest to use a stimulus which has contours in only one meridian, such as a bar grating. Our mode of stimulus pattern generation is similar to that used by Millodot and Riggs. Bars of Polaroid sheet, laid side by side, form a grating which is imaged on the projection screen. The angle of polarization alternates 90° successively from bar to bar. In our experiments, these bars subtended 6 minarc or 14 minarc within a 7° diameter circular field. Light passing through the bars is analyzed by a homogenous Polaroid sheet which

is rotated to produce a sinusoidal alternation of the intensity of the bars at a rate of 7 Hz. A variable speed, regulated DC motor rotates the Polaroid sheet. The average spatial luminance of this test target is always constant, and thus there is no general response to light as with a flash-evoked response.

The 7 Hz stimulus frequency was chosen for three reasons. Both the fundamental frequency and the second harmonic avoid the alpha band (8-13 Hz) of the electroencephalogram, preventing the interference known as "alpha driving." Seven Hz and 14 Hz also show minima in the power spectrum of the random EEG¹³; therefore, an EEG containing a VEP filtered around these frequencies will have a higher signal-to-noise ratio. Recording at high frequencies also allows shorter sweep durations and shorter total recording time for each averaged VEP of the same number of stimuli.

A bipolar electrode configuration was found to be optimal, the active electrode being 2 cm above the inion on the midline. The reference electrode was placed 7 cm above the inion on the midline, and the ground electrode on either (usually left) earlobe. Scalp impedance for all contacts were maintained below 10 K Ω . To avoid spurious electrode polarization and the occasional tingle sensation felt by subjects, and caused by DC ohmmeters, a special low frequency-low current AC impedance meter was constructed for electrode impedance measurements.

The scalp potentials were amplified by two Grass P-15 amplifiers connected in series, filtered with a Krohn-Hite bandpass filter, model #330BR, and summated with a Princeton Applied Research Corporation Waveform Eductor, model TDH-9. The Waveform Eductor is a special-purpose analog computer designed for signal averaging. The averaged VEPs were written out on a Hewlett-Packard dual channel strip chart recorder, model #320, or on a Hewlett-Packard X-Y recorder, model 7035B.

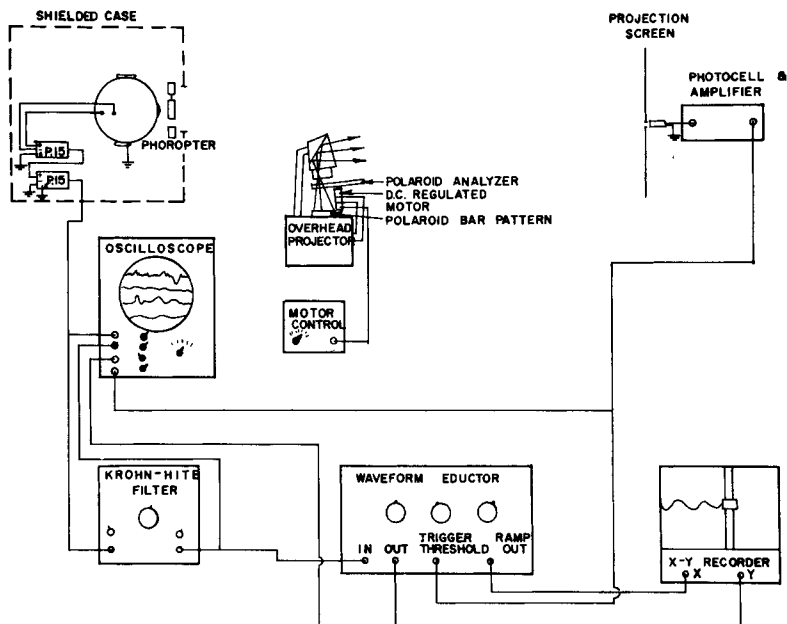


Fig. 1 Schematic diagram of experimental arrangement.

The stimulus was monitored with a photocell placed on one of the bars of the stimuli field. A threshold detector within the Waveform Educator used the sinusoidal photocell output to trigger a sweep. This sinusoidal trigger signal was monitored on a cathode-ray oscilloscope to ensure a consistent effective triggering level. The unfiltered electroencephalogram (EEG), filtered EEG, and summated EEG (which under these stimulus conditions is the VER) were also monitored. Two hundred and ten summations were taken for each VER. Fig. 1 shows our experimental arrangement.

Five female and four male subjects, ranging in age from 19 to 30 years, were tested. Except for refractive error, all had normal vision. Subjective refraction was determined by one of us (G.M.), or the subject's own spectacle R, if recent, was used as the "subjective R" referred to in this paper. Several subjects wore contact lenses during the testing. These are listed in Table 1 by the notation "C.L." It was decided not to test these subjects with their lenses removed as the refractive errors of such eyes are known to be variable soon after contact lens removal. The refractive errors indicated for these subjects are the "residual" errors measured while the contact lenses were being worn.

Table 1

Cumulative results of VER meridional refractometry on all nine subjects, as compared to subjective R and retinoscopic R. Retinoscopies were not obtainable on all subjects. The notation (C.L.) under the subject's initials indicates that the subject was wearing contact lenses during testing. All other subjects were uncorrected. Eye tested is indicated as "R" for right and "L" for left. Accommodative status is denoted as "N" when normal and "C" when paralyzed. Results for both accommodative states are shown when measured.

Subject	Accommodative Status	R Predicted by VER	Subjective R	Retinoscopic R	Eye Tested
J.A.	N C	-2.00-2.00x135 -3.00sph	-2.00-0.25x90		R
D.G.	N C	plano plano	plano-0.25x90	plano-0.25x10	R
L.H. (C.L.)	N	+0.25-0.75x112	plano	+0.25-0.25x85	L
C.M.	N	-0.50sph	plano-0.25x125	+0.25sph	R
A.L.	N C	-0.75-1.50x90 -0.75-1.50-90	-1.25-0.25x90	-1.00-0.50x90	R
M.S. (C.L.)	N	-0.25-0.75x67	-0.25-0.25x 55	+0.25-0.50x60	R
L.T.	N C	-0.50-2.00x157 -1.75-1.50x157	-0.25-0.50x100		R
N.U. (C.L.)	N	+0.50-1.50x144	+0.75-0.25x130	+0.75-0.75x90	L
L.W.	N	plano-2.00x135	plano-0.25x125		R

TESTING PROCEDURES

The subjects viewed the white light stimulus at a distance of 5 meters while seated in a Faraday cage, and were instructed to view the center of the stimulus field, but yet not to fixate any one spot. This we found yielded waveforms of larger amplitude and greater harmonic purity. Various lenses were interposed, with a standard clinical refractor, before the right eye

(usually) while the left eye was occluded.

For subjects C.M., L.W., M.S., N.U., and L.H., initial trials with 15 minarc bars and +4, +2, plano, -2, and -4 D lenses were taken, for each of the 3 meridians, to obtain a gross estimate of refractive error. Refinement of the refractive correction for each meridian was done with a variable series of lenses in $\frac{1}{4}$ D or $\frac{1}{2}$ D steps, and with the 6 minarc bars. A series of lenses would be started from the highest convex value, the power being successively decreased thereafter. Subjects A.L. and D.G. were also tested with normal accommodation as above, but for cycloplegic testing, 1 D steps from +5 D to -5 (except for subject J.A. in which the highest positive was +2 D, the least positive -7 D) were taken for each meridian, with 14 minarc bars only.

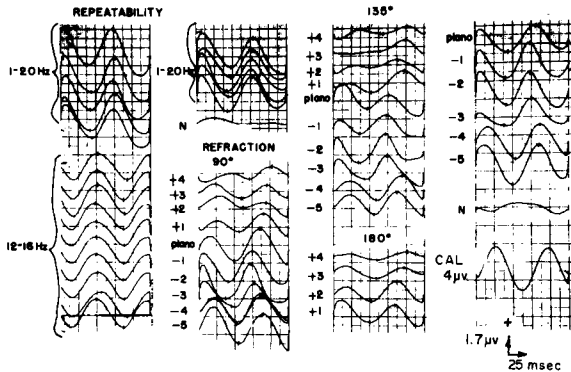


Fig. 2 VERs obtained from subject A.L. with paralyzed accommodation and a 12-17 Hz bandpass. The total lens power before the tested eye is shown at left of each trace with "N" indicating a "noise" trial. The orientation of the bars is indicated for each particular testing sequence; "refraction" indicating the sequence was run for refractive error determination. The terms "repeatability" or "reliability" seen in subsequent figures, indicates when a series of lenses was used for that purpose.

Calibration is shown at right. Calibration signals were obtained from the photocell output, attenuated with a voltage divider, and sent through the system in the same fashion as the biological signals. All calibrations for succeeding figures were obtained in this manner.

Subjects L.T. and J.A. were also tested with only the 14 minarc bars, and in 1 D steps, but with both normal and paralyzed accommodation. This change in procedures was necessary to analyze inconsistencies which appeared in data from subjects C.M., L.W., M.S., N.U. and L.H. When cycloplegia was used, 2 drops (or more if needed) of $\frac{1}{2}$ % cyclopentolate HCL (Cyclogel) was instilled 30 to 45 minutes before testing began. No more than one-half diopter of residual astigmatism was found before or after testing in all cases as measured with the accommodative stimulus "push-up" method.

RESULTS

Averaged waveforms (Figs. 2, 3, and 4) and amplitude and latency versus lens power functions (Figs. 5 and 6) are shown for subjects A.L. and J.A. Subject A.L. (Figs. 2, 3) produced relatively consistent data, typical for most subjects. A few produced less consistent data, such as subject J.A. (Fig. 4). Results of testing with and without cycloplegia are shown in the same figures.

One of the most striking features of the waveform is that the basic frequency of the response is 14Hz, which is double that of the modulation frequency of any one bar. Apparently, a "cortical cycle" is evoked by one change of light for dark, or dark for light, and not by a complete cycle of

dark to light to dark. This is also seen in the report by Millodot and Riggs⁸ mentioned previously. Fig. 2 shows 20 repeated visual evoked potentials for subject A.L., 10 being recorded through a bandpass of 1-20 Hz, and 10 through a bandpass of 12-17 Hz. There is hardly any qualitative waveform change between the two types of VER. There is a total lack of the 7 Hz fundamental frequency.

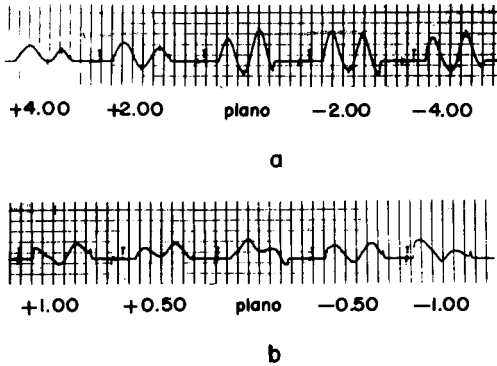


Fig. 3 A sample of VERs obtained from subject A.L. with normal accommodation. 3a shows a sequence of gross lens changes (2 D) on the 14 minarc bar pattern, 3b shows a sequence of small step lens changes ($\frac{1}{2}$ D) on the 6 minarc bar pattern. The bars were always oriented at 180° .

The repeated responses through different bandpasses for subject A.L. (see Fig. 2 under "repeatability") and others were initially intended to test whether a narrow bandpass would improve repeatability over that of a wide bandpass. It was found that the narrower bandpass (12-17Hz) did slightly improve repeatability, and was consequently used for testing subjects L.T. and J.A. at a later time. VERs on subjects C.M., L.W., M.S., N.U. and L.H. were taken earlier with the wider bandpass being used. In Fig. 4 are shown VER repeats with -1, -3 and -5 D lenses on subject J.A.

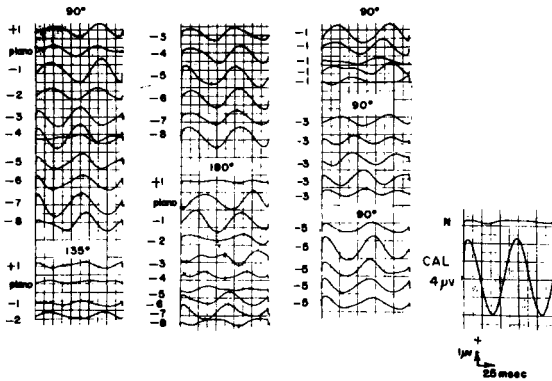


Fig. 4 VERs from subject J.A. with normal accommodation. Calibration shown at right. All other conditions as in Fig. 2

It is evident that the repeatability for subject A.L. (Fig. 2) is considerably better than for subject J.A. It is unlikely that an interaction of the amount of blur with repeatability could have occurred here as repeatability is poor in all 3 lens conditions shown in Fig. 4. The -3 diopter lens condition for subject J.A. should be as reliable as the VEP repeats done on subject A.L.

with full correction, but is not. The lack of repeatability and consistency of the VERs for subject J.A. is also apparent in the graded lens series of Fig. 4.

It should be emphasized here that the term "repeatability" is intended to reflect the validity of the VER within one recording session only, and for a series of successively recorded VERs only. To reproduce identical amplitudes and latencies for this type of stimulus over prolonged periods of time is not a critical factor, and only the relative amplitudes and latencies within one recording session are important. Exact amplitude and latency reproduction is also difficult to achieve due to the multiplicity of variables which can change over time, such as recording methods, electrode placement, growth and skin cornification near recording site (over a period of years), changes in the generator of the VER, and changes in the general physiological make-up of the individual. As long as this class of variables does not change within one recording session, reasonable results should be obtainable. Regarding the long term reproductibility of results, one may be interested in Fig. 5 (subject A.L.) and Fig. 6 (subject J.A.). There was an interval of two months between the normal and paralyzed accommodation experiments for the former, and several weeks between the two experiments for the latter.

Two criteria were used to evaluate which lens provided the optimal correction: trough-to-peak amplitudes, and latency. It is obvious from most records that as the testing lens approaches the optimal correcting lens for any given meridian, the amplitude of the VER increases. A less obvious effect is demonstrated in the results of subject A.L. (Fig. 2) for a series of lenses presented while the subject viewed the bar pattern at a 90° orientation. It can be seen that the first negative trough and second positive peak decrease in latency as the optimal lens value is approached, and then increase as more concave power is added. It is evident that a minimum latency will occur for the best correcting lens. This new criterion¹⁴ appears to be at least as good a predictor of refractive correction as amplitude for subject A.L. The effect was less obvious for subjects J.A., D.G. and L.T. Data on the remainder of the 9 subjects were too incomplete to show this effect. The latency criterion was the only basis used to estimate refractive error in subject J.A. as the relationship between amplitude and contour sharpness appeared to break down completely.

While latency decreased predictably for clearer vision, it was not necessarily a minimum at best correction. In some cases, more concave power or more convex power was indicated. Fig. 6 for subject J.A. is one which shows a minimum latency for lenses more concave than his best correction.

Waveform amplitudes were usually measured from the first negative trough to the second positive peak. Relative latencies were determined by using the maximum trough and peak points of the amplitude measurements. The latency of each of these was measured from the beginning of the summed VER, added together, and divided by two. It must be emphasized here that these latencies are only in reference to the beginning of the VER, and not directly to the stimulus itself. Absolute phase lag is largely unknown and difficult to identify by our methods and was not measured.

Figs. 5 and 6 show the amplitude and latency functions of lens power for

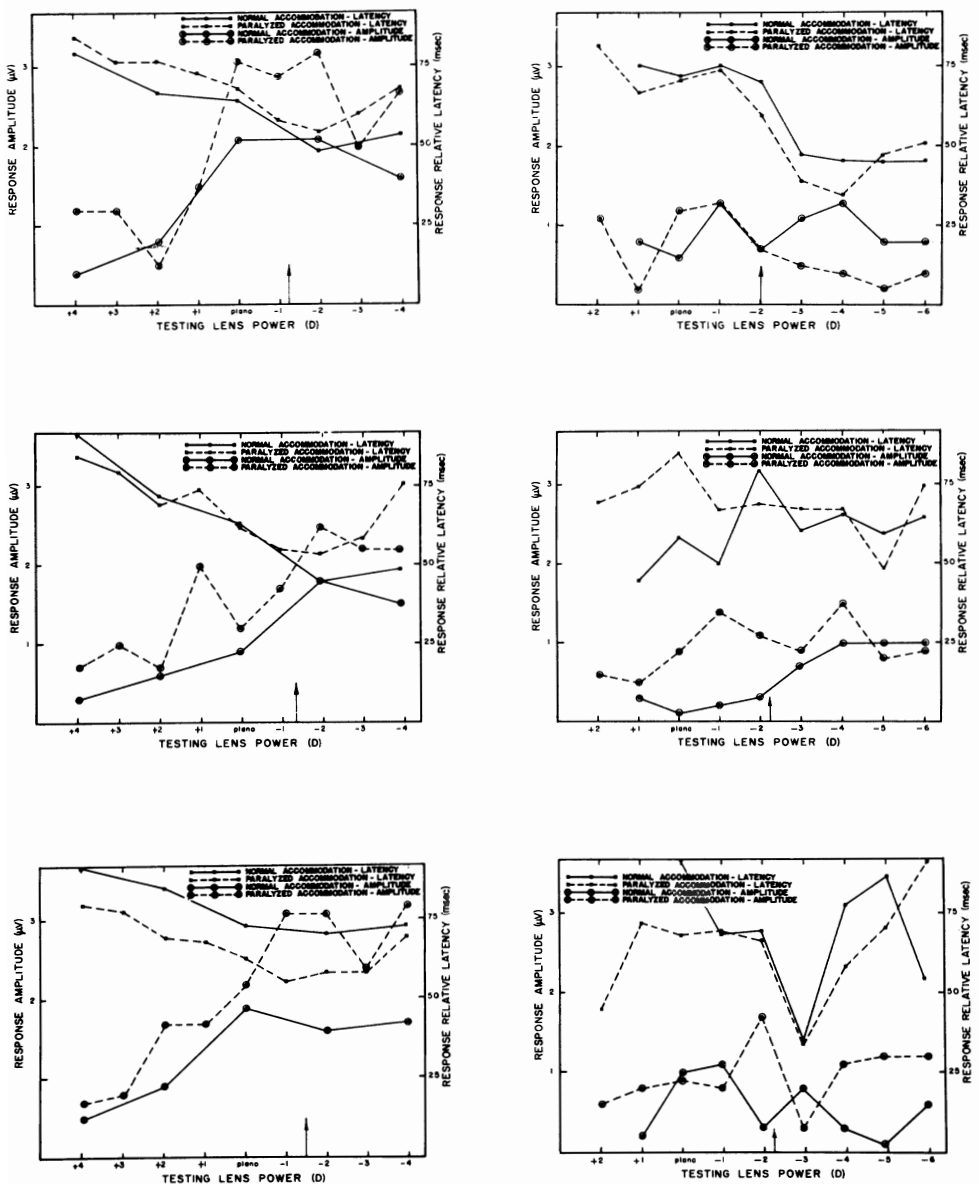


Fig. 5 (left) Amplitude and latency functions of lens power for subject A.L. The solid line indicates testing with normal accommodation, the broken line paralyzed accommodation. Functions with concentric rings represent amplitude measurements, and functions with squares indicate relative latency measurements. The arrow on each abscissa indicates the refractive error of the eye in that particular meridian, as determined by subjective examination. The amplitude and latency functions for bars oriented at 180°, 135°, and 90° are shown at top, middle, and bottom respectively. The power of any one meridian would be measured at an orientation 90° from that of the bar orientation.

The subjective R for subject A.L. was $-1.25 -0.25 \times 90$.

Fig. 6 (right) Amplitude and latency functions for subject J.A. All other parameters are as in Fig. 5. The subjective R for subject J.A. was $-2.00 -0.25 \times 90$.

subjects A.L. and J.A. The arrow on each abscissa indicates the power of the best subjective correction in that meridian.

In testing subjects C.M., L.W., M.S., N.U. and L. H. it became obvious

that inconsistency was going to be a serious problem. The 6 minarc bar pattern appeared to produce poorer results than the 14 minarc pattern, and was eventually dropped from the testing procedure. Refractive error estimates were then made with the 14 minarc pattern alone. Fig. 3 shows this problem pictorially. The screening lenses (Fig. 3a) would suggest, in this case, that the best correcting lens might be in the interval from +2 D to -2 D. A series of 5 lenses used in combination with the 6 minarc pattern produced the results in Fig. 3b. It was not possible to pick out the best correction from this series of VERs. This example was a typical case for most subjects on whom the 6 minarc bars were used. One or two subjects did appear to show reliable results with the 6 minarc bars, but too few lenses were tried to demonstrate a consistent effect.

It was considered that fluctuating accommodation might be producing the inconsistencies evident with subjects C.M., L.W., M.S., N.U. and L.H. We thus tested subjects D.G., L.T., A.L. and J.A. under cycloplegia and under normal accommodation. It is obvious from Figs. 5 and 6 that the VERs were equally inconsistent under cycloplegia as with normal accommodation. An interesting phenomenon appeared for subjects L.T. and A.L. (Fig. 5 for subject A.L.) whose VERs can be seen to be as large for over-corrected concave lens conditions, with accommodation paralyzed, as for clear conditions. This occurred even though the subjects reported that the target was quite blurred, and residual accommodation was measured and found to be less than $\frac{1}{2}$ D. It is also worth noting that the waveform latencies for subjects A.L. and L.T. showed the predicted increase in latency (as described earlier) with concave lenses even though amplitudes were large. Apparently, latency is controlled independently of amplitude under these stimulus conditions. We plan to investigate this phenomenon further in the near future. Subject D.G. showed the expected drop in amplitude under cycloplegia and concave lenses. Table 1 shows the predicted prescriptions, calculated by VER meridional refractometry, for all 9 subjects as compared to their best subjective prescriptions, and retinoscopies when available.

DISCUSSION

As already pointed out, the inconsistencies apparently inherent in this VER method make it difficult to use it as a sensitive refraction method. The causes of these inconsistencies are difficult to single out, but taken collectively, they appear to be a problem of obtaining an adequate signal-to-noise ratio. Narrowing down the sources of noise becomes a considerable problem because of the demands placed on the VER in defining refractive error. In the strictest sense, noise is the intervening of electrical activities which are not directly related to the stimulus. In the broadest sense noise is anything in the system which limits the VER accuracy as a method of eye refraction. Waveforms obtained from subject A.L. (Fig. 2) illustrate this problem. The waveforms are quite clean and free of extraneous artifact, but vary in amplitude. It may be that these summated VERs represent variations of the signal itself, possibly because of an internal mechanism such as attention. The narrow bandpass did slightly improve repeatability in subjects L.T. and A.L., indicating the influence of extraneous activity near the frequency of interest, but this would not appear to account for all the variability present. The

problem of variability would seem to be a result of recording for prolonged periods of time, which sometimes occurred for our recording sessions. The repeated VERs for subject A.L. were performed in a relatively short period of time, e.g., 10 minutes, and thus may not reflect the variability evident for longer recording periods. These factors in combination may produce the fluctuations which are present in Figs. 5 and 6. In theory, these functions should be smooth single-peaked curves with a maximum at the best correcting lens. The extent to which these functions vary probably reflects the influence of the above factors. Whether or not these factors could ever be eliminated is another matter. It is easy enough to narrow bandpass and increase summations, but controlling attention and its physiological concomitants is not an easy task, especially in clinical situations. It is also not desirable to increase the number of summations per VER due to the increased time required. A stimulus which would produce larger signals would then be in order. The checkerboard used by Millodot and Riggs⁸ is known to produce larger amplitude than a bar grating^{15,16} and this factor alone may account for their claim of ± 0.25 D sensitivity. Preliminary studies in our laboratory indicate that both the amplitude and latency criteria may be as sensitive as ± 0.25 D using the checkerboard. Astigmatic corrections cannot as easily be tested with such a stimulus compared to a grating, however. There are several variations of stimulus parameters which may allow increased sensitivity and short duration recording periods, and yet still be used with meridional refractometry. All of them use checkerboard-like stimulation to some degree. They are as follows:

1. The equations published by Brubaker et al., require knowing the mean spherical refractive error of the eye, the refractive error of the 45° meridian and the refractive error of the 90° meridian. We chose to measure the refractive errors of the 180° , 45° , and 90° meridians with the bar stimulus, and to average the 180° and 90° values to obtain a mean sphere value. A better method may be to use a checkerboard stimulus to find the mean spherical error initially, and then to use bar stimuli for the 45° and 90° meridians. This approach would have the advantage of providing a more accurate estimate of mean spherical error (for those eyes with small or moderate amounts of astigmatism), thus providing a good starting point for the meridional estimates. Knowing initially the mean spherical error would allow fewer trials in the 45° and 90° meridians, as the great majority of astigmatism would fall within ± 2 D of the mean sphere value. More summations, therefore, could be used for each bar-generated VER without increasing the total examination time.

2. A stenopaic slit could be used in combination with a checkerboard stimulus to isolate the meridional components of the checkerboard-generated response. The checks could be oriented with their sides at 90° - 180° to obtain the mean sphere values and 90° meridional values, and at 45° - 135° for the second meridional value. The stenopaic slit would be used for the meridional testing only. Limitations may be anticipated in obtaining enough light through the slit, and in obtaining a significant response to meridional blur from the checkerboard stimulus. Whether or not these anticipated limitations will be significant can only be resolved through more research.

3. Because of technical limitations it was necessary for us to record an entire sequence of VEPs with one type of stimulus before proceeding to the next. This method assumes a stability of the VEP which does not seem justified. It would seem more reasonable to present the three test stimuli (checkerboard, 45° bars, 90° bars) and an amplitude control stimulus (flickering diffuse light) in rapid succession (on the order of several seconds each) within one lens testing condition. This approach, while technically formidable, should minimize the effects of physiological variations in time.

Another limiting factor in our methods may be bar size. It is clear that large bars limit the sensitivity of the VER, and that smaller bars would need to be used. A problem arises if such is done, however, because small bars produce small signals, and consequently need more summations. The inconsistency illustrated in Fig. 3b may be a manifestation of this. Further studies in our laboratory, however, have shown that smaller bars can give reliable results if the initial non-blurred contrast is not too high. Spekreijse¹⁷ has shown that VERs generated with counter-phase-modulated checks will saturate with as low as 20% contrast in many normal subjects. Campbell¹⁸ limited the contrast of sinusoidally modulated bars to 30% maximum contrast, suggesting nonlinear VER properties above that contrast. These results would suggest that little predictable increase in the VER amplitude would occur after lenses have improved the contrast to the saturation level. Consequently, the contrast of a bar grating should be limited before optical change of contrast is undertaken.

We have found that we can increase VER sensitivity of bar grating focus to ± 0.50 diopters if contrast and bar size are optimally controlled.

The technical problem of measurement of waveforms is another factor to consider. Surely the subjective estimation of peak amplitude and latency by the examiner is subject to error, especially with noisier waveforms. This problem can be overcome by more sophisticated waveform measurement techniques. For instance, more objective and accurate measurement of the phase and amplitude of the VER could be made by cross-correlating the VER with a reference sine wave of the same fundamental frequency as the VER, but with a non-shifting phase. In essence, this method separates that component of the VER which has the same frequency as the reference sine wave, making the VER easier to measure.

As stated above, bar grating estimates of refractive error are probably limited to ± 0.50 diopters for any one meridian, sampling a general patient population. The mean spherical error should be a maximum of ± 0.25 diopters. We have not achieved this sensitivity for the data we have shown because of non-optimal use of stimulus, recording, and measuring methods, as further testing in our laboratory has indicated. Even using optimal methods, sensitivity to astigmatic errors may be low, and for two reasons: (1) The visual system is relatively insensitive to meridional (astigmatic) blur, as evidenced by the lower sensitivity to bar defocus than to checker defocus, and the common clinical observation that an uncorrected astigmatic error will have much less effect on acuity than a spherical error of the same dioptric value; (2) The method of meridional refraction itself will tend to exaggerate inaccuracy of astigmatic power and axis determination if errors are made in

meridional power estimates. For example, given an eye with a known refractive error of -3.00 DS, and the following VER meridional power estimates: $P_{90} = -3.50$, $P_{45} = -2.50$, $P_{ms} = -3.00$, a predicted prescription of -2.25 DS = -1.50 DC x 68 could occur where in fact there is not an astigmatic error. This is, of course, a "worst case" analysis, and most determinations would be more accurate than this. It is apparent that either more meridians would need to be included in the calculations, in order to reduce the effect of power estimate errors, or astigmatic error estimates would have to be ignored if less than -1.50 DC were predicted. We have not explored these possibilities, but the latter would certainly limit this VER method to rough screening for astigmatic elements in a refractive error. We still believe the VER to be very sensitive to mean spherical focus, approaching subjective sensitivity in a normal and cooperating adult, and probably more sensitive than retinoscopic determinations of refractive error.

Another point of interest is whether or not this VER method has a bias for more plus power or more minus power than subjective results. The average mean spherical errors for nine subjects as determined by this VER method is -0.87 D, while subjective determinations have an average mean spherical error of -0.60 D in the same nine individuals. This difference is hardly significant considering the low sensitivity bar grating determination of refractive error used in this experiment.

The question also arises concerning the rationale of using the standard subjective as a comparison for the VER. The visual stimuli used to obtain a subjective prescription are considerably different from the VER stimulus. It may be that a refractive correction determined by subjective meridional refractometry with an oscillating bar-grid pattern may be different and/or less sensitive than the standard subjective. While this possibility was not systematically studied, it was noted that of those subjects who were asked, all reported difficulty in determining optimum focus subjectively on the 14 minarc oscillating bar-grid pattern, and for some, that large lens steps were required (e.g., 1.00 D) to produce a significant effect.

Comparing our results with those of others would seem to verify their claims for sensitivity, assuming stimulus and measurement techniques are optimized. Millodot and Riggs⁸ reported 0.25 D sensitivity for a checkerboard stimulus, and our results with checkerboards appear comparable. Comparisons with the Ludlam and Meyers⁷ results are difficult to make because of the great difference in stimulus technique (they use stroboscopic flashes) employed, but they appear to be able to obtain better results on astigmatism, claiming a maximum power error of 0.50 D (our best is about 1.50 D maximum power error). Axis determination will be a function of the amount of the astigmatic error, and is meaningless until a significant power error is present. Given a minimum cylindrical error of 1.50 D, axis determination within ± 15 degrees should be obtainable using methods outlined in this paper.

Our results obtained on subjects with paralyzed accommodation suggest that accommodation was not a significant factor in producing the variability of VERs for lens values differing from the optimum. The large amplitudes attained under concave lens blur and cycloplegia were not studied systematically and are a subject for future research. In light of our results, one can

speculate if chromatic aberration and spherical aberration, which is usually positive for the unaccommodated eye,¹⁹ is a factor maintaining large amplitudes under concave lens blur. Blue light in the stimulus, combined with a large pupil, could maintain a good VER of the bar grid even though several diopters of concave lens power were added in addition to the best subjective lens power. The differences between subjects for the concave lens functions would reflect differences in spherical aberrations of these eyes.

SUMMARY AND CONCLUSIONS

The use of sinusoidally modulated bars and the amplitude criterion of the VER can be used for gross screenings of refractive error. They may not be sensitive enough for refined refractive estimates within the constraints of clinical practicality. Sensitivity appears to be limited to ±1 D for any given tested meridian, using methods initially outlined in this paper. The source of inconsistencies which limit its sensitivity appear to be inherent in the problem of obtaining a good signal-to-noise ratio, optimizing the stimulus, and using optimum measurement techniques.

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APPENDIX A

Equations for Meridional Refractometry (Brubaker, et al.^{11,12}

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

$$C = \pm 2 \cdot \text{sqr} \{ [M(S) - M(45)]^2 + [M(S) - M(90)]^2 \}$$

$$\Theta = -(\frac{1}{2}) \cdot \text{atn} \{ [M(S) - M(45) / M(S) - M(90)] \}$$

If M(90) - M(S) is greater than or equal to 0, then let $\Theta = \Theta + 90$

If M(90) - M(S) is less than 0 and M(45) - M(S) is less than 0, then let $\Theta = \Theta + 180$

If M(90) - M(S) is less than 0 and M(45) - M(S) is greater than or equal to 0, then let $\Theta = \Theta$

APPENDIX B

C-8K FOCAL @ 1969

```
01.10 TYPE " * * * * * COMPUTERIZED REFRACTOMETRY * * * * * ",!!!
01.20 TYPE " PLEASE TYPE DATA WHEN REQUESTED. TO HALT PROGRAM,";!
01.30 TYPE " ENTER ALL ZEROS AS DATA INPUT.";!!!

02.10 TYPE " PLEASE TYPE DATA INPUT:";!
02.20 ASK "M(0)",M(0)
02.30 ASK "M(45)",M(45)
02.40 ASK "M(90)",M(90)

03.10 IF (M(0))4.1,3.2,4.1
03.20 IF (M(45))4.1,3.3,4.1
03.30 IF (M(90))4.1,7.1,4.1

04.10 SET A=[M(0)+M(90)]*0.5
04.20 SET C1=[M(45)-A]↑2+[M(90)-A]↑2
04.30 SET C=2*FSQRT(C1)
04.40 SET S=A+(C*0.5)
04.45 IF (C) 4.5,4.46,4.5
04.46 TYPE %6.03 S,"SPH"!!!
04.47 GOTO 2.1
04.50 IF (M(90)-A) 4.6,4.8,4.6
04.60 SET P1=[M(45)-A]/[M(90)-A]
04.70 GOTO 4.9
04.80 IF (A-M(45)) 4.82,4.86,4.86
04.82 SET P=-135.0
04.84 GOTO 5.1
04.86 SET P=-45.0
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04.88 GOTO 5.1
04.90 SET P=-.5*FATN(P1)*180/3.1415
05.10 IF (M(90)-A) 5.2,5.3,5.4
05.20 IF (M(45)-A) 5.3,6.1,6.1
05.30 SET P=P+90
05.40 SET P=P+90
06.10 TYPE %6.03 S,-C,P,!!
06.20 GOTO 2.1
07.10 TYPE " * * * PROGRAM COMPLETE * * * ",!
07.22 QUIT
    
```

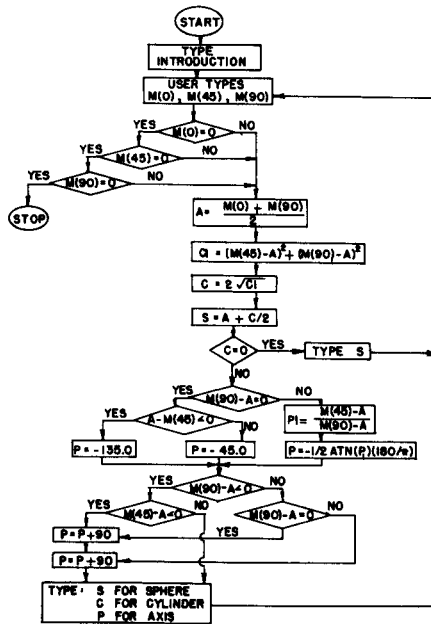


Fig. 7 Flow Chart for program in appendix B.

REFERENCES

- Marg, Elwin and Rebecca Ng, Optometrists' human and computer assistants, J. Occupat. Med., 14 (5): 357-362, 1972.
- Marg, Elwin, Gary Liberman, and Edward R.F.W. Crossman, Towards computer-assisted optometry, Optom. Weekly, 60 (45): 17-20, Nov. 6, 1969.
- Crossman, Edward R.F.W., Phiroze J. Nagarvala, and Elwin Marg, An information-theoretic analysis of clinical refraction, Am. J. Optom. and Arch. Am. Acad. Optom., 48 (5): 391-406, 1971.
- Crossman, Edward R.F.W., Peter J. Goodeve, and Elwin Marg, A computer-based automatic method for determining visual acuity, Am. J. Optom. and Arch. Am. Acad. Optom., 47 (5): 344-355, 1970.
- Marg, Elwin, E.R.F.W. Crossman, P.J. Goodeve, and H. Wakamatsu, An automatic case-history taker for eye examination, Am. J. Optom. and Arch. Am. Acad. Optom., 49 (2): 105-112, 1972.
- Duffy, Frank H. and Roy H. Rengstorff, Ametropia measurements from the visual evoked response, Am. J. Optom. and Arch. Am. Acad. Optom., 48 (9): 717-727, 1971.
- Ludlam, W. M. and R. R. Meyers, The use of the visual evoked response in objective refraction, Proc. N.Y. Acad. Sci., 34 (2): 154-170, 1972.
- Millodot, Michel and Lorrin A. Riggs, Refraction determined electrophysiologically; responses to alternation of visual contours, Arch. Ophth., 84 (3): 272-278, 1970.
- Harter, M. Russell and C. T. White, Effects of contour sharpness and check-size on visually evoked cortical potentials, Vision Research, 8 (6): 701-711, 1968.
- Laurance, L., General and Practical Optics. London, The School of Optics, Ltd., 1924, pp. 593-602.
- Brubaker, Richard F., Robert D. Reinecke, and Jack C. Copeland, Meridional refractometry. I. Derivation of equations, Arch. Ophth., 81 (6): 849-853, 1969.
- Brubaker, Richard F., Robert D. Reinecke and Joel S. Newman, Meridional refractometry. II. Data reduction, Arch. Ophth., 83 (5): 570-573, 1970.

13. Johnson, L., A. Lubin, P. Naitoh, C. Nute, and M. Austin, Spectral analysis of the EEG of dominant and non-dominant alpha subjects during waking and sleeping, *Electroencephal. and Clin. Neurophysiol.*, 26 (4): 361-370, 1969.
 14. Berkley, Mark A. and David W. Watkins, Grating resolution and refraction in the cat estimated from evoked cerebral potentials, *Vision Res.*, 13: 403-415, 1973.
While our paper was in preparation, Berkley and Watkins published their report on cat VEPs using grating stimuli, and mentioned that lens blur affected VEP latency, but did not qualitatively or quantitatively describe or explain the phenomenon.
 15. Armington, John C., Simultaneous electroretinograms and evoked potentials, *Am. J. Optom. and Arch. Am. Acad. Optom.*, 47 (6): 450-459, 1970.
 16. Rietveld, W.J., W.E.M. Tordoir, J.R.B. Hagenouw, J.A. Lubbers and Th. A.C. Spoor, Visual evoked responses to blank and to checkerboard patterned flashes, *Acta Physiologica et Pharmacologica Neerlandica*, 14 (3): 259-285, 1967.
 17. Spekrijse, H., Analysis of E.E.G. Responses in Man Evoked by Sine Wave Modulated Light. The Hague, W. Junk, 1966.
 18. Campbell, F.W. and J.J. Kulikowski, The visual evoked potential as a function of contrast of a grating pattern, *J. Physiol.*, 222 (2): 345-356, 1972.
 19. Ivanoff, A., *Les Aberrations de l'Oeil*. Paris, Revue d'Optique, 1952.
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