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ABSTRACT

Previous studies have indicated that visual acuities of normal infants can be estimated with good accuracy using swept spatial frequency visual-evoked-potentials (VECPs). In this report we describe acuity measurements obtained with this technique from 304 examinations performed on 135 children having various visual disorders. When possible, two or more different stimulation frequencies (8, 12, 15 or 24 contrast reversals/sec) were used in each patient, and three to eight sweep VECPs were obtained from each patient under each simulation and recording condition. High correlation coefficients (0.94 – 0.96) between the acuity estimated on each patient from either the single sweep giving the best visual acuity (BSS) or from vector averages (VeA) of the EEG data obtained from several sweeps confirmed previous findings in normal infants. We also found high correlation coefficients among BSS recorded at different temporal frequencies (0.79 – 0.97) and among comparisons of BSS or VeA acuity to optotype visual acuity (0.6 – 0.89). Children with clinically undetectable optokinetic responses showed lower visual acuity estimated by BSS than those who demonstrated optokinetic nystagmus. We conclude that the sweep VECP is a valid method, giving estimates of acuity which correlate well with optotype acuity and correspond well to other clinical findings, and that it can be useful in the clinical management of nonverbal patients.

INTRODUCTION

A variety of psychophysical and electrophysiological methods have been developed for measuring the visual acuity of infants and toddlers. The major difficulty has been the length of time necessary to acquire a sufficient number of responses to yield reliable measurements. Recently, attention has been focused on swept spatial frequency visual-evoked-cortical-potentials (Sweep VECPs). In this technique, the pattern element size is “swept” from large to small sizes over a range spanning the acuity limit. The sweep VECP provides rapid sensory threshold measurements and requires less cooperation from the subject than do the other currently available tests.

Sweep VECP acuity estimates during the first year of life of normal infants have been reported to be in qualitative agreement with the results of previous studies of infant acuity development but approximately three to
five times higher than measurements obtained using other
techniques in which pattern appearance or pattern
reversal stimulation were employed. Comparisons of
visual acuities estimated from single runs with those
based upon vector averages of evoked potentials recorded
under the same test conditions have indicated high
reliability of sweep VECP acuity measurements in normal
infants. Abnormal acuity development in infantile
esotropia and high correlations between optotype acuity
and grating acuity in amblyopia have also been
demonstrated with this technique.

Several issues remain to be addressed before the clinical
value of the sweep VECP can be definitively established.
For example, published data from normal subjects haveeen obtained using linear sweeps across spatial
frequencies. Linear sweeps can be justified when the
acuity is known and the sweep range can be appropriately
set to optimize sampling density within a range of spatial
frequencies near the acuity limit. But what of patients
whose acuity is unknown or cannot be estimated solely on
the basis of their age, and with whom practical
considerations may limit the time available for testing?
Might not logarithmic sweeps across spatial frequencies
be more appropriate? Also, what about temporal tuning of
swept spatial frequency acuity estimates? How might
acuity measurements be influenced by temporal tuning?
These are some of the issues we are beginning to address
in our laboratory that cannot be answered by studies
limited to normal subjects.

We now report acuities measured in 135 children
between 3 weeks and 11 years of age. We used four
different temporal frequencies for sweep VECP
stimulation. The single sweep giving the best visual acuity
(BSS) was compared to the acuity estimated from a vector
average (VeA) calculated from VECP data of all runs
performed under the same stimulation and recording
conditions. Correlations between BSS acuities among
different temporal frequencies were calculated. We also
compared available clinical data such as optotype visual
acuity (VA) and optokinetic nystagmus (OKN) to the
acuity estimate obtained from sweep VECP recordings.

MATERIALS AND METHODS
All patients examined with the sweep VECP technique
in our laboratory within the last two years were included
in the study. We tested 135 children between the ages of 3
weeks and 11 years (mean natal age 4.3 years). In several
patients, recordings were repeated on different
examination days, so results from 304 examinations are
reported here. Ten patients had strabismus without
amblyopia, 26 had amblyopia (11 strabismus, 9
anisometropia and 6 deprivation), 9 aphakia, 1 cataract,
25 nystagmus, 7 albinism, 7 retinopathy of prematurity, 3
retinal colobomas, 1 retinitis pigmentosa, 1 Leber's
amaurosis, 2 microphthalmia, 2 glaucoma, 2 optic nerve
hypoplasia, 2 optic nerve atrophy, 3 glioma of the optic
nerve and chiasma, 4 hydrocephalus, 4 cortical blindness,
1 microcephaly, 4 delayed visual maturation, 2 hysterical
amblyopia, and in 6 patients the diagnosis was unclear. In
addition, 12 normal subjects were included in the study.
Due to poor cooperation or to technical problems no results
could be obtained in 14 out of the 304 examinations. In 74
patients, OKN was evaluated using a handheld OKN
doctor with eye movement recordings or visual observation.
The OKN drum was presented at a distance between 20 to
40 cm with stripe width corresponding to about 2 to 1.7 log
min arc. Patients were categorized as follows: (0) those
who had no OKN response; (1) those with an OKN
response in one to three directions; and (2) those with a
normal OKN response. Optotype visual acuity was
obtained in 49 patients using either Snellen, Allen or
tumbling E charts. In children who could not discriminate
the optotypes, counting fingers (width of one finger about
1.5 cm) at 50 cm was estimated to correspond to a visual
acuity of 0.04, hand motion (width of the hand about 8 cm)
at 50 cm was considered equivalent to a visual acuity of
0.006 and light projection or lower visual acuity was
assigned a value of 0.001 (Dawson, personal communication).

All sweep VECP acuity data presented here were
obtained using the Digital Infant Visual Assessment
(DIVA) system developed by Christopher Tyler, Anthony
Norcia, and their colleagues at the Smith Kettlewell Eye
Research Foundation in San Francisco, California with
minor modifications made by one of the authors (MGF).
Details of the apparatus and analysis techniques can be
found elsewhere. Briefly, children were presented with
96% contrast, sinusoidal, luminance gratings with space
average luminance of 24 cd/m². The gratings were
modulated at rates of 8, 12, 15 or 24 reversals per second.
During a 10 second period, the spatial frequency of the
reversing grating was incremented logarithmically in 20
steps such that the highest spatial frequency presented
was approximately 24 times the lowest one. Thus, the
range of spatial frequencies depended upon the viewing
distance, with a 200 cm distance yielding spatial
frequencies ranging from 1.3 to 30.9 cycles per degree. The
stimuli were presented on a SONY PVM-122 video monitor
with a 25 cm (horizontal) by 20 cm (vertical) rectangular
display field. The viewing distance was selected for each
patient so as to place their anticipated acuity within the
upper third of the sweep range.

VECPs were simultaneously recorded on two
independent channels using a bipolar electrode derivation
with OZ referenced to positions 3 cm above CZ on the
midline (channel 1) and directly to the right of OZ (channel
2). The ground electrode was placed on CZ.
Preamplification of the EEG was achieved using Grass
P511K A.C. preamplifiers with gain of 1,000 to 10,000
and half-amplitude band-pass filter settings of 0.1 Hz and 10
KHz.

An Apple II+ computer, equipped with a hardware
multiplier, sampled the EEG data with 8 bit D/A
conversion at 200 Hz. A Discrete Fourier Transform
(DFT) was applied to the EEG data to measure amplitude and phase over a 1 Hz band centered on the second harmonic of the visual stimulation frequency (i.e., measurements of the EEG components of 16, 24, 30, and 48 reversals per second were measured for corresponding stimulation rates of 8, 12, 15, and 24 reversals per second). In addition, amplitude and phase measurements were also obtained of an adjacent frequency band which should not contain visually evoked activity (centered at 18, 26, 32 and 50 reversals per second for stimulation at 8, 12, 15 and 24 reversals per second, respectively) to estimate background EEG activity unrelated to visual stimulation during the trial. From these “noise” measurements, an amplitude criterion for the evoked potential “signal” was determined. The noise-frequency measurements were also used to reject portions of the records with muscle spike or movement artifacts from subsequent analysis. Plots of the linearly scaled EEG “signal” and corresponding “noise” frequency amplitudes are provided in the upper panels and their phase values (between -π and +π) in the lower panels of the printed results (see Figure 1).

During testing, the examiner judged whether or not the infant was fixating the screen. Data collection could be interrupted by activating a switch connected to the computer. Afterwards, acuity was determined by linear extrapolation of the appropriate portion of the VECP amplitude versus spatial frequency function. A (least squares) regression line was fitted to the data between the last spatial frequency peak and the point at which the amplitude at the signal frequency dropped below approximately 1.5 times the noise amplitude. An acceptable spatial frequency peak was defined as the highest spatial frequency peak at which the amplitude of the response exceeded 3 times the average amplitude of the respective noise measurement. Additionally, the phase of the response within the range of spatial frequencies used for acuity estimates had to be either constant or, as visual system latencies have been found to increase with smaller stimuli, gradually lagging the stimuli.

Our procedure was to attempt at least 3 to 6 trials before moving to a new condition. Data from all single runs performed under the same testing conditions were included within each vector average. Patients were examined with the right or left eye alternately covered or, when they had central visual system disorders, with both eyes open.

High correlations have been demonstrated in normal subjects between the highest estimate of acuity obtained
from the best single sweep (BSS) and that obtained from the vector average (VeA) of data from these runs. Since variability in a patient’s attentiveness and muscle activity can conspire to lower the measured acuity, but is unlikely to raise it, it has been suggested that the best clinical strategy is to accept the highest acuity derived from single sweep recordings as the best estimate of a patient’s acuity. We compared BSS and VeA acuities obtained from our patients to test the validity of extending this approach from normal subjects to patients tested in a clinical setting.

Acuity measurements in patients with more than one sweep VECP recording were separated by time intervals between 3 and 14 months. During such time intervals it is likely that their visual acuity changed due to visual system maturation or to changes in the course of the disease. For this reason, we considered it inappropriate to use results from multiple examinations for test/retest reliability within subjects.

Pearson correlation coefficients and linear regressions were calculated to compare the BSS to the VeA under each temporal frequency, to compare BSS among different temporal frequencies, and to compare BSS or VeA to the optotype visual acuity. For computational purposes, all acuity measurements were transformed to their corresponding values in log minutes of arc in accordance with previously published observations regarding the scaling of visual acuity measurements. For these statistics, only one value was included for each test condition from each patient. We (arbitrarily) selected this measurement to be that obtained from the right eye on the first testing session.

If this measurement was unavailable, results from the left eye were taken, and if there was no monocular data available, binocular acuity measurements were used. If no data from the first examination day were available, data were selected from the next testing session following the same procedure.

RESULTS

1) Original recordings of two patients

Patient 1, an 8-year-old girl, was referred because of a decrease in visual acuity (20/50 Snellen chart right and left eye) and to rule out optic nerve degeneration as its cause. Sweep VECPs were recorded with a 15 reversals per second stimulation rate. The BSS of her right eye is represented in Figure 1A. Her spatial frequency tuning functions (upper panel solid line) show peaks at 6 and 13 c/d, and the estimated acuity was 22.2 c/d (Snellen equivalent 20/27). The vector average of 4 single sweeps (Figure 1B) had a similar (dual peak) form and yielded an acuity estimate of 20.9 c/d (Snellen equivalent 20/29). From the left eye, the BSS visual acuity estimate was 20.2 c/d (Snellen equivalent 20/30) and the VeA 19.2 c/d (Snellen equivalent 20/31). In the consecutive ophthalmological examination no pathology was found and the patient read the 20/20 line of the Snellen chart with each eye. A diagnosis of hysterical amblyopia was made.

Patient 2, an 8-year-old boy with albinism and congenital nystagmus, had the BSS (Figure 1C) and the VeA (Figure 1D) recorded at 15 reversals per second in the left eye. Both the BSS and VeA showed one peak at about 1.5 c/d and yield acuity estimates of 2.3 c/d (Snellen equivalent 20/260) and 2.6 c/d (Snellen equivalent 20/230), respectively. His Snellen acuity of the left eye was 20/200.

2) Comparison between BSS and VeA acuities at different temporal frequencies

Figure 2A represents the relationship between the BSS and the VeA acuities estimated from recordings obtained using a 12 reversals per second stimulation rate. Most of the data points lie close to the regression line indicating a good correlation between BSS and VeA acuity estimates. The (0.91) slope and (.121) y-intercept of the (least squares) regression line are also indicative of a close correspondence of BSS and VeA estimates.

In Table 1, correlation coefficients and equations of the regression lines are listed for comparisons of BSS and VeA acuity estimates obtained using each of four different stimulation frequencies. High correlation coefficients were found for each temporal frequency, with the regression
equations indicating slightly better correspondence at the 15 reversals per second stimulation rate.

3) Comparison between BSS acuities among different temporal stimulation frequencies

Given the high correlation between BSS and Vea acuities and the fact that we have more data available for BSS, we restricted comparisons among different temporal frequencies to the BSS acuity measurements. Figure 2B shows comparisons between the BSS obtained under stimulation with 8 reversals per second and 24 reversals per second. Correlation of 0.81 was found between values obtained under these two temporal frequencies. For visual acuity estimates under a resolution of 0.6 log min arc (corresponding to Snellen acuity better than 0.23) the linear regression line indicates that stimulation with 8 reversals per second tended to yield somewhat higher estimates of acuity than did stimulation at 24 reversals per second. In contrast, for patients with low visual acuity, the visual acuity estimated by stimulation with 8 reversals per second was lower than at 24 reversals per second.

Table 2 shows the correlation coefficients and equations of the regression lines for BSS acuity measurements when compared between each combination of temporal stimulation frequencies employed in this study.

Correlation coefficients were high for all comparisons and varied between 0.79 and 0.97. For patients with good visual acuity the linear regression data indicate that lower temporal stimulation frequencies generally result in slightly higher estimates of acuity than do higher temporal frequencies. In contrast, for patients with low visual acuity, the Vea gave slightly higher estimates of acuity.

4) Comparison between optotype acuity and BSS acuity estimates

Figure 2C represents the values obtained by optotype acuity testing and those estimated from the BSS at a 12 reversals per second stimulation frequency. In one measurement the BSS acuity was clearly overestimated and, in another measurement, underestimated. The other values all lie fairly close to the regression line. For patients with high visual acuity (below resolution of 1.2 log min arc or above Snellen acuity of 0.06) the regression equation indicates that acuities estimated by BSS were generally somewhat lower than the optotype acuity, while for patients with lower visual acuity the BSS slightly underestimated the optotype acuity.

Table 3 shows the correlation coefficients and equations of the regression lines relating optotype acuity and acuity estimated by BSS at different temporal stimulation...
TABLE 3

BSS Versus Optotype Acuity at 8, 12, 15, 24 Reversals/Second

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<thead>
<tr>
<th>n</th>
<th>Correlation Coefficient Linear Regression</th>
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<tbody>
<tr>
<td>8BSS/VA</td>
<td>18</td>
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<tr>
<td>12BSS/VA</td>
<td>31</td>
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<tr>
<td>15BSS/VA</td>
<td>21</td>
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<tr>
<td>24BSS/VA</td>
<td>14</td>
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TABLE 4

VeA Versus Optotype Acuity at 8, 12, 15, 24 Reversals/Second

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<tr>
<th>n</th>
<th>Correlation Coefficient Linear Regression</th>
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<tr>
<td>8VeA/VA</td>
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<td>15VeA/VA</td>
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<td>24VeA/VA</td>
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6) Comparison between OKN responses and BSS acuities

Among patients whose optokinetic nystagmus (OKN) was evaluated with the handheld OKN drum, most of our available electrophysiological acuity data was obtained using 12 reversals per second and 15 reversals per second BSS contrast reversal rates. Means and standard deviations from these acuity data were calculated within the three OKN categories of patients. Figure 3 shows that the mean acuity estimate by BSS is clearly lower in category 0 (no OKN response) than in category 1 (with OKN response in 1 to 3 directions) and category 2 (normal OKN response). The variability of acuity measurements among patients in category 0, however, is also considerably higher than in either of the other two categories.

DISCUSSION

We examined a large group of patients with various visual disorders. Although many patients with conditions unlikely to give good VECP recordings (such as central visual system disorders and nystagmus) were included in the study, our results confirm that the sweep VECP method provides high reliability and high correlation with optotype acuity. Less than 5% of the examinations failed to be completed; half of these were due to poor cooperation on the part of the subject, the other half due to technical difficulties.

The high correlation coefficients between measurements obtained from the BSS and VeA (>0.9 for all four temporal frequencies) confirm previous results found in normal infants. Having used at least 3, but in most examinations more than 5, single sweeps for calculating the VeA in our experiments, this high correlation between BSS and VeA acuity estimates implies relatively high reliability of the
sweep VECP measurements. We also found reasonably high correlations among BSS acuities measured using different temporal stimulation frequencies. Between the lowest (8 reversals per second) and highest (24 reversals per second) temporal frequency used in our study, the correlation was coefficient 0.81. This agrees with the good correspondence of acuities previously reported for normal subjects tested with swept spatial frequency stimulation at 12 reversals per second and 20 reversals per second. It is noteworthy that the slopes of linear regression comparing all BSS acuities among different temporal frequencies indicate that the acuity estimates tend to be somewhat higher when stimulating with slower stimulation rates. This is not in agreement with previously published measurements obtained using the preferential looking method, where a tuning with highest acuity at temporal frequencies of 7.5 reversals per second and 14 reversals per second was found. These psychophysical findings, however, were obtained from normal infants and the fact that we examined patients with visual disorders might account for this discrepancy.

Recognition acuity measured psychophysically using optotypes and BSS VECP grating acuity measurements showed high correlations. No clear differences were found between BSS and VeA acuity estimates. Although, surprisingly, we found that the correlation between acuity measured psychophysically with optotype stimuli and that estimated electrophysiologically from sweep VECPs was lowest for VeA acuity estimates using the 15 reversals per second stimulation rate, no clear pattern between the relationship of the psychophysical and electrophysiological acuity measurements and temporal stimulation frequency is evident in our data. The recordings from the patients represented in Figure 1 show that the BSS and VeA yielded slightly lower estimates of acuity than was measured psychophysically using optotype stimuli. The slopes of our linear regression data further show that this underestimation tends to occur in patients with better acuities. This might be explained by a rolloff in contrast of our (video) stimulus display monitor for high spatial frequency gratings and not be a characteristic of swept spatial frequency acuity estimates per se. This possibility will be studied further in our laboratory.

The BSS acuity estimates obtained at 12 reversals per second and 15 reversals per second were clearly lower and considerably more variable in the infants with no OKN response than in those with OKN responses in 1 to 3 directions or in those with normal OKN responses. The difference between patients with OKN in 1 to 3 direction and with normal OKN response was minimal. This can be explained by the fact that most of the children in the category with OKN response in 1 to 3 direction were nystagmus patients and had a VA comparable to the group with normal OKN response. Since the OKN responses were examined within our group of nonverbal patients, our findings support the hypothesis that sweep VECP acuity estimates are consistent with clinical findings in infants and toddlers.

In patient 1 (Figures 1A and 1B) we showed that malingering could be detected with the sweep VECP method. However the sweep VECP acuity findings of about 20/30 underestimated the Snellen acuity of 20/20 found in a later examination of that patient. This corresponds to the underestimation by sweep VECP acuity found generally in our patients.

However, for subjects familiar with the sweep VECP technique, malingering is certainly possible. By chewing, for example, or gritting the teeth, one of our examiners tested should that the noise level could be raised to the point at which no reliable acuity measurements could be obtained. Voluntary over-accommodation could also be used by the malingering patient to produce artificial low estimates of acuity.

Being the first group to report swept spatial frequency acuities obtained from a large, diverse sample of patients in a clinical setting, a few general comments regarding our experience with the procedure may be helpful. Despite the fact that most swept spatial frequency VECP acuity studies to date6-9 have employed linear sweeps across spatial frequencies, it has been our experience that this is very often impractical in clinical testing of abnormal infants. Ideally, one would like to first estimate, using log sweeps, the acuity of each eye to establish a range of spatial frequencies to be swept linearly that would result in each eye sampling approximately the same number of spatial frequencies within the portion of the range used to estimate acuity. This is rarely possible due to time restrictions and, for this reason, we usually employ logarithmic (equally perceptible step) sweeps of spatial frequency for testing patients from whom no other reliable estimates of visual acuity are obtainable. Also, although the current technique requires considerably less cooperation of subjects than other methods for measuring vision in infants, its practical clinical utility is still related to patient cooperation. This cooperation can be enhanced by establishing rapport with the infant and parents, and by using techniques for recording and electrode preparation that are rapid. Even so, we have found that children between one and four years of age can be extremely difficult to test. This should not dissuade one from using sweep VECPs for patients when knowledge of their visual capabilities may influence the diagnosis or treatment of their disorder. The same limitation applies to all other currently available electrophysiological and psychophysical methods for measuring infant visual function.

We conclude that in our group of patients with various visual disorders the sweep VECP gives estimates of acuity which correlate well with optotype acuity and correspond well to clinical findings. The swept spatial frequency VECP provides a relatively rapid means of obtaining electrophysiological estimates of grating acuity, requiring only brief periods of cooperation on the part of the patient, and can be useful in the clinical management of nonverbal patients or those otherwise unable to respond to traditional psychophysical acuity tests. However, further
work is needed to establish the sweep VECP reliability for specific visual disorders, particularly for conditions unlikely to give good VECP recordings such as amblyopia, optic nerve diseases and central disorders.

REFERENCES


