VARIABILITY AND DEVELOPMENT OF A NORMATIVE DATA BASE FOR SACCADIC EYE MOVEMENTS

A. TERRY BAHILL,
ALLAN BROCKENBROUGH
and
B. TODD TROOST

From the Department of Electrical Engineering, Carnegie-Mellon University and the Department of Neurology, University of Pittsburgh Medical School, Pittsburgh, Pa.

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Variability and development of a normative data base for saccadic eye movements

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The duration, peak velocity, and acceleration of the saccadic eye movements of 13 normal subjects are plotted as functions of saccadic magnitude. The apparent peak velocity of a saccadic eye movement is sensitive to the algorithms used to calculate the velocity. The velocity channel filter should have zero phase shift and a cutoff frequency between 60 and 100 Hz in order to limit noise but pass all the signal information. Some subjects fatigue rapidly; their parameters fall outside the normal range of values.

Key words: saccadic eye movements, main sequence, duration, velocity, acceleration, filtering, differentiation, power spectra, fatigue, bandwith, linearity

Saccadic peak velocity–magnitude-duration parameters, called the main sequence parameters,[1, 2] have been used to define saccades. Eye movements were called *saccades* if their peak velocity–magnitude-duration parameters matched normative data. This technique has been used for regular saccades,[3–6] closely spaced saccades,[7] overlapping saccades,[8] non–Hering's law saccades,[9] fast phases of nystagmus,[10–12] voluntary nystagmus,[13] dynamic overshoots,[14] and fractionated saccades in internuclear ophthalmoplegia.[15] Many of these studies used different normative data bases. In this paper we try to explain possible reasons for the variability in these data bases.

From the Department of Electrical Engineering, Carnegie-Mellon University and the Department of Neurology, University of Pittsburgh Medical School, Pittsburgh, Pa.

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Reprint requests: A. Terry Bahill, Biomedical Engineering Program, Department of Electrical Engineering, Carnegie-Mellon University, Pittsburgh, Pa. 15213.

The great utility of these peak velocity–magnitude-duration parameters has prompted questions of how much they are affected by fatigue, intersubject and intrasubject variability, instrumental noise, low-pass filtering of the data, and by the algorithms used to compute the parameter values. We answered these questions in defining the quantitative aspects of a normal data base.

Developing a consistent set of valid normative saccadic eye movement data that could be used for intralaboratory comparisons was difficult. First, many normal subjects in a homogeneous age group had to be recorded. Second, the eye movements of fatigued subjects had to be rejected. This required a visual examination of the velocity profile of each individual saccade. Third, peak velocities and durations had to be plotted as functions of saccadic magnitudes, not of target displacements. Fourth, the velocity waveform, not the position waveform, had to be used to define the beginning and end of each saccade. Fifth, zero-phase digital filters and algorithms had to be used to calculate velocity. Sixth, Bode diagrams of the filters had to be measured and plotted, particularly for the velocity channel. Seventh, it had to be

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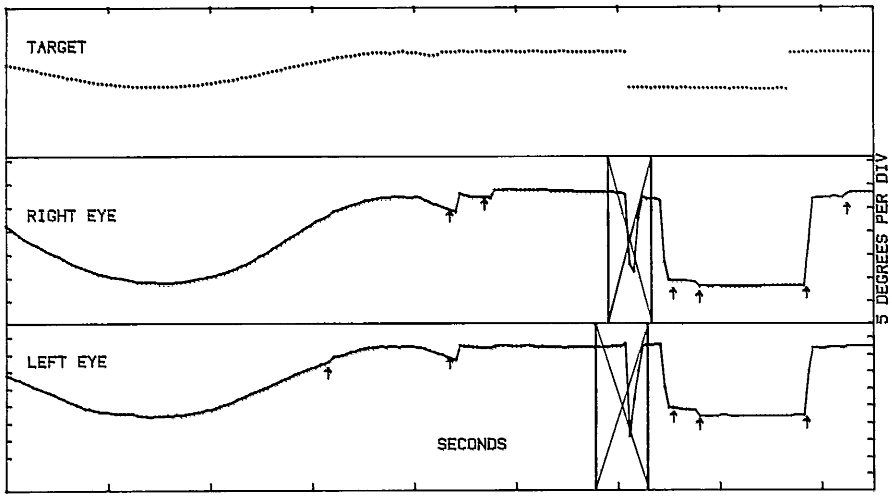

Fig. 1. Target and eye positions at the start of a typical recording session. The sinusoidal tracking is included to ensure linearity. Candidate saccades are pointed to by the arrows. The operator has rejected the eye blink (boxes with X) that occurred just before saccadic tracking began. The target jumps were 20 deg. Rightward movements are represented by upward deflections in all our figures. This figure shows a soft saturation, a nonlinearity, in the left eye channel, as illustrated by the attenuation of the two microsaccades of left eye on extreme right gaze.

demonstrated that the recording system was linear for the entire range of measurement. A data base such as this has not been previously published. Some authors[1] published data for only one subject; they measured[16] but did not publish their velocity channel bandwidth. Some authors[12, 17] published mixed electro-oculogram (EOG) and photocell data and did not explicitly state the bandwidth of the eye velocity records. Some authors[18] did not measure their bandwidths, and others[19] used EOG and mixed the results of measurements of one eye alone and the movement of the two eyes averaged together.

There are two purposes of this article: to provide a valid normative data base for human saccadic eye movements and to explain differences in previously published data.

Methods

Saccadic refixations in response to discrete target movements were measured. The target waveforms were generated either with an analog function generator or with a computer. The target was a small red laser dot (3 mm diameter) projected on a white screen 57 cm from the subject. The target voltage drove a galvanometer that had a small mirror attached. The movement of the mirror deflected the laser beam to produce the horizontally moving dot on the screen. Subjects viewed the target binocularly in a dimly illuminated room. Informed consent was obtained after the equipment and the experiment were explained to the subjects.

The movement of each eye was measured with standard photoelectric techniques.[14] The linear range for the measurement of horizontal eye movements extended ±10 deg from primary position. The system was linear for 20 deg of eye rotation. This limit on linearity was prescribed by the size of the iris and the covering of the iris by the eyelids. It is difficult, but not impossible, to obtain valid data for saccadic eye movements larger than 20 deg with this technique.[8] Instrument noise was less than 1 mv and was, therefore, smaller than signals produced by eye movements of 1 min arc, which were on the order of 30 mv. Saccades as small as 3 min arc have been recorded on this equipment.[20] The target movement and the movements of the eyes were amplified (0 to 300 Hz bandwidth), passed through an analog to digital converter sampling at 1000 Hz, and stored on a disk in the computer.

It took 2 to 15 min to adjust the photocells and

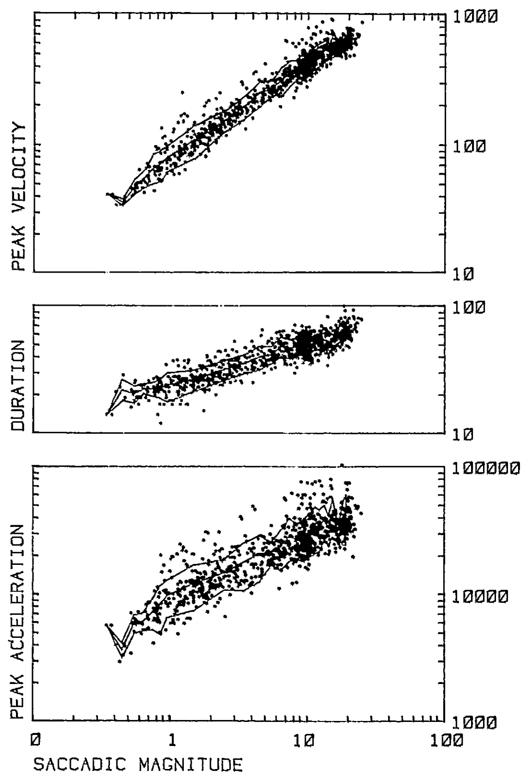

Fig. 2. Main sequence diagrams showing peak velocity, duration, and the first peak acceleration as functions of saccadic magnitude for the saccadic eye movements of 13 normal subjects. The magnitudes were computed from records with a bandwidth extending from 0 to 300 Hz; peak velocities and durations were derived from records with an 80 Hz bandwidth; accelerations were derived from 60 Hz bandwidth records. The units are degrees for magnitude, degrees per second for peak velocity, milliseconds for duration, and degrees per second squared for acceleration.

obtain linear recordings over the central range. The subject was allowed to rest for a few minutes and was then asked to track a random amplitude square wave target movement for 3 min. A 3 min rest period was allowed, and then the calibration and the 3 min test were repeated. Finally, the calibration test was repeated and the session was over.

The peak velocity-magnitude-duration parameters are changed primarily by fatigue.[8] Fatigue is used here in a broad sense to include muscle fatigue, tiredness, and inattention. We have avoided these effects by keeping our recording sessions short, about 3 min each, and by ensuring mental alertness through verbal admonishments such as, "Track very carefully now." We believe that a continuous interactive process is extremely important in obtaining consistent, valid data. Intrasubject and intersubject variability is significantly reduced by such attention to detail. We therefore monitored the analog records as the data were being taken. If the data were noisy or nonlinear they were discarded and the equipment was readjusted. These techniques have been successful in minimizing aberrant effects.

An important aspect of the calibration routine was the tracking of a slow (0.2 Hz) sinusoid. A sinusoid of this frequency is very easy to track and most humans can track it with very few saccades. These records were inspected to ensure that the recording system was linear. With a linear system the eye movements looked sinusoidal, and microsaccades could be seen in each channel at both extremes of gaze. It is not sufficient to have the subject look at a few selected targets to check for linearity, since soft saturation at the end points and discontinuities will be missed. At least one cycle of this sinusoidal tracking was included in every disk file of data to ensure linear recordings (Fig. 1). Visual inspection of this sinusoid by the experimenter is a necessary and sufficient test to detect common instrumentation nonlinearities.

Saccadic data analysis was performed on a PDP 11/34 computer with interactive graphics programs. The eye movement data were displayed on a graphics terminal where the operator specified which sections of the data were to be averaged together to define the voltages corresponding to each of the fixation points. This produced the deg per volt calibration factors. Typically 5 to 10 sec of data were averaged to obtain each of these factors. The velocity as a function of time was calculated for each eye and was stored in a file called the velocity channel. The acceleration as a function of time was calculated from the velocity data with similar algorithms and filters. Saccadelike events, where the velocity exceeded 20 deg/sec, were marked while in the interactive graphics mode. The operator either accepted the event if it appeared to be a saccade or discarded the event if it appeared to be a blink or an artifact.

The magnitude, duration, peak velocity, and size of the first peak acceleration were computed for each saccade. A two point central difference algorithm and a 80 Hz, zero-phase, low-pass filter were used to compute the velocity as a function of time. The beginning and end of each saccade was defined by this velocity trace. Since the peak velocity of a saccade occurs just about in the middle of the saccade, the time of peak velocity was determined. Then the points before and after the center of the saccade where the velocity was 5 deg/sec were located. When the velocity dropped into the ±5 deg/sec noise band, we said the eye had reached zero velocity. These points were defined to be the beginning and the end of the saccade and were used to determine the magnitude and duration of the saccade. Defining the saccadic size by means of the zero-velocity points rather than the presaccadic and postsaccadic positions eliminated the effects of glissades and thus greatly reduced the scatter in the data.

We used a 80 Hz (3 dB point) filter in the velocity channel. It was a rectangular window in the frequency domain corresponding to 5 lobes of a sinc function in the time domain, ±17 data points.[21] Its frequency response is shown in Fig. 4. The maximum attenuation in the passband was 1.2 dB, and the maximum gain in the passband was 0.3 dB. This filter had 6% overshoot when excited with a step input. Since normal eye movements do not look like step responses, this presented no limitations. The same filter was used for the acceleration channel, but the 3 dB point was reduced to 60 Hz. When higher cutoff frequencies were tried, the computed peak accelerations changed, and the acceleration records became noisier. We did not believe that the peak accelerations computed with the higher bandwidths were more accurate. The 60 Hz cutoff frequency was the best compromise between noise and high-frequency information.

There were two reasons why we sampled at a rate as high as 1000 Hz: it allowed saccadic duration to be estimated within 1 msec, and it allowed a velocity channel bandwidth of over 100 Hz. A 1000 Hz sampling rate yields a 500 Hz Nyquist frequency. Therefore all signal and noise components above 500 Hz had to be removed with analog filters before sampling. We used 300 Hz analog filters (20 dB/decade roll off). To calculate velocity we used a two point central difference algorithm, $2h\dot{y}(i) = y(i + 1) - y(i - 1)$, where h, the sampling interval, is 1 msec. This algorithm acts as a low-pass filter that is shown 4 dB at 250 Hz. It has no phase shift. For an analog-to-digital converter operating at 200 samples per second, this velocity algorithm would remove all frequencies above 50 Hz. Furthermore, for this algorithm there is an optimal sampling rate that gives the most accurate velocity estimates; this rate depends on the accuracy in evaluating the original function. The 1000 Hz sampling rate is optimal for the accuracy with which we can evaluate eye position.

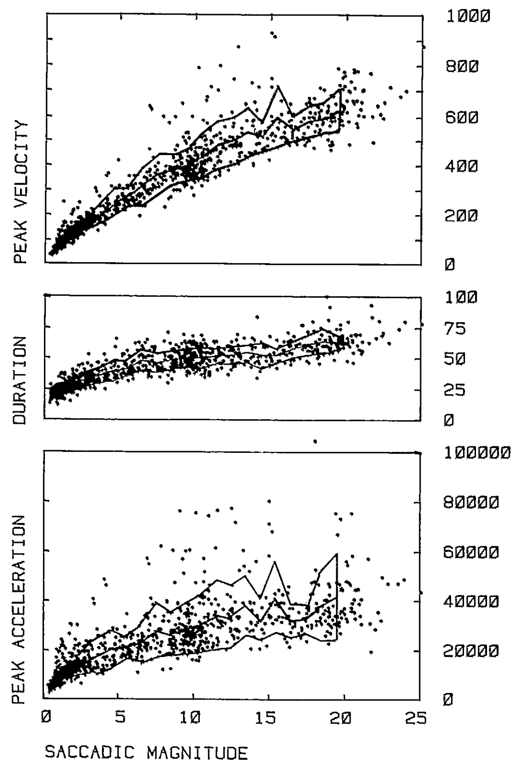

Fig. 3. Same saccadic data of Fig. 2 plotted with linear coordinates.

Table I

Saccadic magnitude (deg)	*Peak velocity and S.D. (deg/sec)*	*Duration and S.D. (msec)*
5	261 ± 42	42 ± 8
10	410 ± 67	51 ± 8
15	499 ± 43	54 ± 7
20	657 ± 78	64 ± 6

Results

Our normative data base contains over 900 saccadic eye movements from 13 normal subjects ranging from 20 to 35 years of age. Figs. 2 and 3 show the peak acceleration, the peak velocity, and the duration all as functions of saccadic magnitude. The peak velocity and the duration were computed from the velocity data, which had a bandwidth of 80 Hz; the magnitude was derived from 300 Hz bandwidth eye position data by timing data derived from the velocity channel; and acceleration was derived from 60 Hz bandwidth

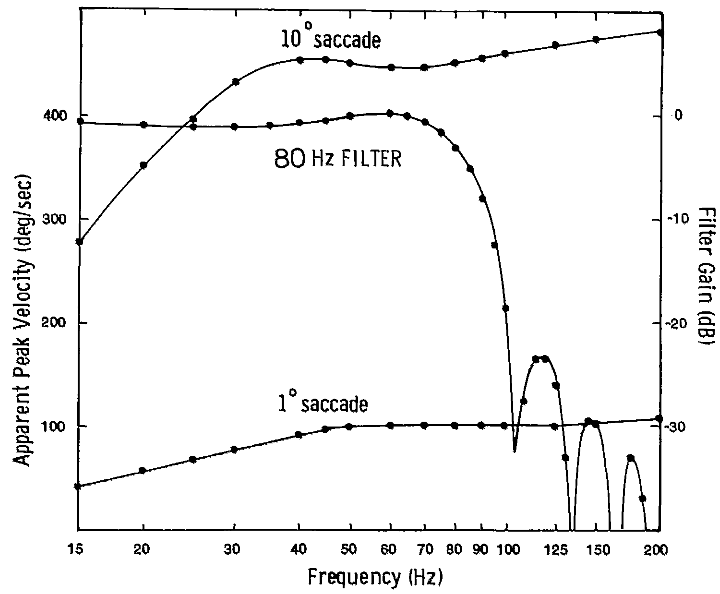

Fig. 4. Apparent peak velocity of two typical saccades as a function of the low-pass filter cutoff frequency, and the response of our digital velocity channel filter. The optimal velocity channel filter should have a cutoff value above 60 Hz so that the apparent peak velocity is not attenuated, but below 100 Hz where computational noise increases the apparent peak velocity.

data. The solid lines are the means and one standard deviation on each side of the mean. Table I provides numerical values for a few saccadic sizes.

An equation that fits the data is:

$$\dot{\theta}_{max} = 684\ (1 - e^{-0.1\Delta\theta})$$

The parameter values shown in Figs. 2 and 3 are very sensitive to the bandwidths of the instrumentation. Low-pass filtering at various frequencies can effect the apparent peak velocity and the apparent duration. The apparent magnitude can also be affected, depending on the algorithm used. Fig. 4 shows the apparent peak velocity of two saccades as a function of the cutoff frequency of our velocity channel filter.

When the cutoff frequency of our velocity channel filter was varied, the apparent peak velocity of most saccades behaved as shown in Fig. 4. It increased as the filter cutoff frequency increased from 15 to 50 Hz and remained relatively constant as this frequency increased from 50 to 100 Hz. We were surprised to see that varying the cutoff frequency of the velocity channel filter in the range from 40 to 60 Hz would have an affect on the apparent peak velocity, since when we calculated the power spectrum of a saccade we found little energy above 40 Hz (Fig. 5). But then we realized that it was not the power spectrum of the position channel that we should be studying, but rather the power spectrum of the velocity channel. Fig. 5 shows these two power spectra for a typical 10 deg saccade. The power spectrum of the velocity channel is broader than the spectrum of the position channel. The velocity spectrum of the left eye is not down 40 dB until 74 Hz. Therefore the velocity channel filter may decrease the apparent peak velocity of a saccade unless its cutoff is 74 Hz or more. The gradual rise in the apparent peak velocity curve of Fig. 4 above 100 Hz is a consequence of the differentiation algorithm and quantization noise. A velocity channel filter with a cutoff between 60 and 100 Hz seems to be optimal. The shape of the apparent maximum acceleration plot was similar to the apparent peak velocity plot.

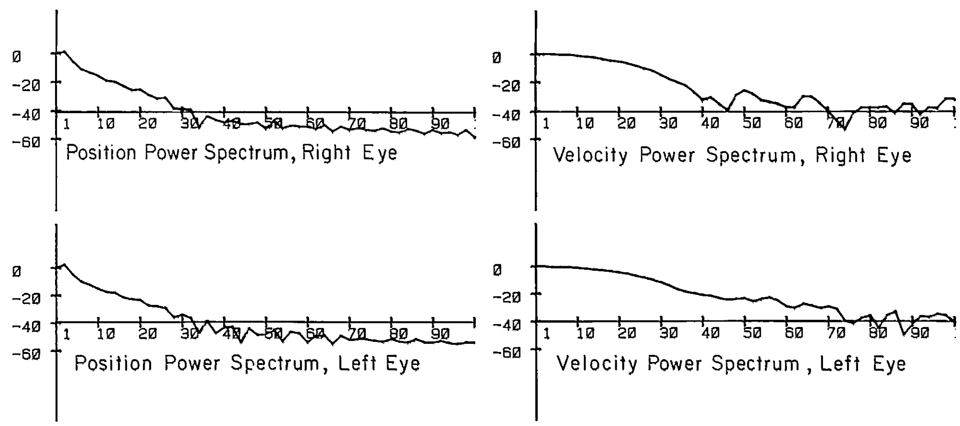

Fig. 5. Power spectral density functions for a typical saccade. The velocity spectrum for the left eye has significant power out to 74 Hz. Such large differences between the spectra of the right and left eyes are not uncommon. Power is in decibels (dB) and frequency is in hertz (Hz).

How many significant digits are there in our calculated values of magnitude and peak velocity? The biggest source of noise, and the only step involving a qualitative decision by a human, is setting the calibration levels to get the degrees per volt calibration factors. We had two experimenters do this 16 times on 3 separate days. The largest difference was 1.3%, with a 0.2% S.D., so that we can say with 95% confidence that our data are reproducible to ±0.4%. This means that the magnitude of a 10 deg saccade may vary from run to run in the second digit after the decimal point, but the first digit after the decimal point will not vary. For magnitude we list the first digit after the decimal point. The analog-to-digital converter has 12-bit resolution; this fact also implies that the first digit after the decimal place is significant but that the third digit cannot be fully resolved. For peak velocity the digit in the units place is subject to variation on repeated trials. For example, a velocity of 411 deg/sec may actually be 410 or 412 deg/sec. (The theoretical maximum error of our numerical algorithm is also 1 deg/sec.) This implies that the 67 deg/sec S.D. of our data was due to human eye movement variability and not our data analysis programs. Because we sampled every millisecond, our average error in duration was 1 msec.

In order to understand the large variability in saccadic parameters reported by others, on 2 separate days we recorded the slowest subject used by Schmidt et al.[18] We included his normometric[22] saccades (e.g., saccade 6 in Fig. 6) in our data base.

Initially an automatic processing routine was used. It showed that half of the eye movements were more than 1 S.D. below the mean; many were apparently 3 and 4 S.D. below the mean. When such a quick look at the data reveals abnormalities, a detailed examination of the velocity profiles of the individual eye movements is called for.

This inspection of the velocity traces showed that eye movements in the first 30 sec of the session were normometric saccades within 1 S.D. of the mean; after this, none of the movements was normometric.

Fig. 6 shows eye movements recorded 6, 49, and 61 sec after the start of one session. It is easy to see that if movement 49 were treated as a 19 deg saccade (because the target jump was 19 deg) a great deal of variability would be added to the data. The peak velocity of movement 49 (460 deg/sec) would be much too slow for a 19 deg saccade, and its duration of 109 msec would be much too long for a 19 deg saccade. However, if this eye movement were treated as a 10 deg, 55 msec, 460 deg/sec saccade followed by a 9 deg, 54 msec, 333 deg/sec saccade, then little variability would be introduced into the data. The large glissade appended to the dynamic

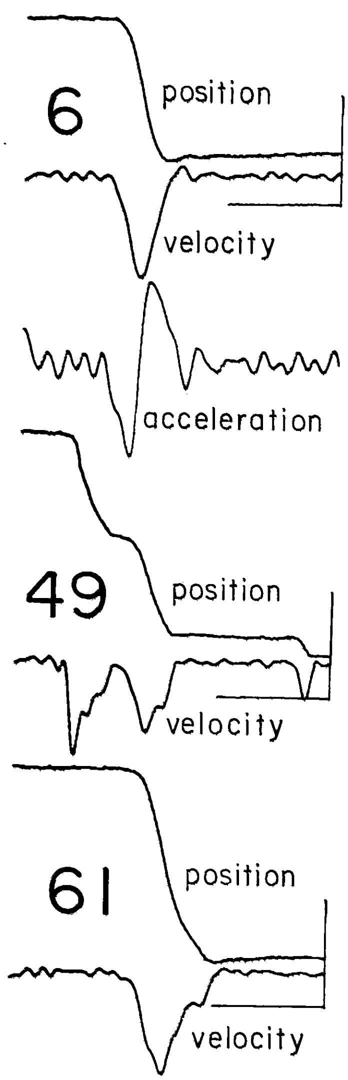

Fig. 6. Saccadic eye movements of a subject entering a state of fatigue. The records are from sixth, forty-ninth, and sixty-first seconds of the recording session. The saccade of record *6* is a normometric saccade that is within 1 S.D. of the mean shown in Figs. 2 and 3. The eye movement of record *49* is composed of two closely spaced saccades. The eye movement of record *61* has a dynamic saccade of 15 deg and a glissade of 4 deg. If the peak velocity of such a movement were said to be the peak velocity of a 19 deg saccade, a great deal of variability would be added to the data. The calibration bars represent 10 deg, 500 deg/sec, 30,000 deg/sec^2, and 100 msec. Bandwidths were 0 to 300 Hz for position, 0 to 80 Hz for velocity, and 0 to 60 Hz for acceleration. The photocells were adjusted quickly and consequently the data are noisy.

saccade in record 61 offers a more subtle example of how the variability of saccadic parameters will be increased if the velocity traces are not used to monitor for fatigue.

The saccadic deterioration was similar in both recording sessions. Once fatigued, this subject's fixations became unstable and smooth pursuit tracking was mostly saccadic.

Humans make thousands of saccades a day. However, they are not repetitive in timing and amplitude, and they are seldom larger than 15 deg in amplitude.[23] A long recording session containing large saccades can fatigue humans. However, none of the other 27 patients and normals we have recorded this past year has fatigued as rapidly as the subject whose data are shown in Fig. 6.

Discussion

The particular computer algorithm used can affect the saccadic parameters. On one occasion the velocity records of a typical saccade were derived (1) with a finite-impulse response, noncausal, zero-phase, rectangular-window digital filter, with a cutoff frequency of 55 Hz and a spread of ±50 points (msec), and (2) with a fifth-order, recursive, linear-phase, digital, Butterworth filter with a cutoff of 55 Hz.[21] The peak velocities and durations derived with use of the two filters were almost the same; these measurements were not affected by the phase shift. However, the magnitudes calculated with the linear-phase filter were in error. The beginning and ending times of the saccade were determined on the velocity record and were then transferred to the position trace in order to calculate saccadic magnitude. A phase shift between these records produced errors. For the linear-phase filter, the calculated starting point was always too late, thus making the saccade seem too small. The calculated ending point was also too late; however, this made the saccade appear either too large or too small depending on whether or not the eye movement had overshoot. Hence the errors in magnitude were stochastic. Use of a linear-phase filter would have increased the standard deviation of the data. The results obtained with the zero-phase filter were more accurate, and the standard deviations of the data were smaller.

We recommend the following overall bandwidths for saccadic eye movement data: 0 to 300 Hz for position, 0 to 80 Hz for velocity, and 0 to 60 Hz for acceleration. Larger bandwidths produce larger standard deviations because of biological, instrumental, and computational noise. Smaller bandwidths produce variability between data bases. Zero-phase digital filters are best. If analog filters must be used, then Butterworth filters with the above bandwidths could be used. However, timing information could not be transferred between the position and velocity channels.

It is very important that the bandwidths be given when quantitative parameters for saccades are reported. However, it is not sufficient to give only the bandwidth of the recording system. The differentiators have dynamics, and interlaboratory comparisons can not be made unless the frequency characteristics of these differentiators are known. It would be best if this velocity channel bandwidth were measured by putting sinusoids in and measuring the sinusoids coming out. Because this bandwidth depends upon system bandwidth, sampling rate, the velocity algorithm, and the velocity channel filters, theoretical calculation of this bandwidth would be difficult.

The analog and digital filters of Baloh et al.[19] matched each other very well. They used 35 Hz analog filters on their data. They tried higher frequency filters and saw no effect on the apparent peak velocity. One of the reasons was that they used a 50 Hz digital filter and their velocity algorithm acted as an 89 Hz filter. Neither was flat in the pass band. The cascade of these two digital operations had a 3 dB point at 35 Hz. If they had increased their sampling rate, then the digital operations would have had higher frequency cutoff values and there would have been some difference in apparent peak velocity as the cutoff frequency of the analog filter was increased.

The differentiation algorithm acts as a lowpass filter. To evaluate the velocity at point i we used the data at points 1 msec before and after point i. For a 1000 Hz sampling rate, this yields a bandwidth of 223 Hz. We could change the algorithm to use points 4 msec before and after the point i. This algorithm would have a bandwidth of 56 Hz. This would have reduced the accuracy of the velocity computation and increased the high frequency noise, but it would have saved the time and expense of the extra velocity channel filter. We did not do this originally because we wanted to see and understand each operation separately.

For noisy data, the 5 deg/sec criterion for defining the beginning and end of the saccade did not work well. In these cases we found the points where the velocity was 5% of the peak velocity and then added 1 msec to the start and 3 msec to the end of the saccade. This new time interval was then used to calculate the magnitude and the duration of the saccade. The values of 1 and 3 msec were chosen because they predict the zero velocity points for noise-free records of saccades between 1 and 20 deg. For noisy data, the bandwidth of the position channel was reduced from 300 to 125 Hz, the bandwidth of the velocity channel was reduced from 80 to 60 Hz, and the bandwidth of the acceleration channel was reduced from 60 Hz to 45 Hz. The noisy data algorithm and filters were not used to compile this normative data base; they were sometimes used in analyzing the data of clinical patients.

The peak velocity main sequence diagram has been more useful than the duration diagram. Therefore, in this study, we tried to get accurate, consistent velocity data. If we had focused on the duration data, we would have used different algorithms. For example, our velocity channel filter in conjunction with defining the beginning and the end of a saccade with the zero-velocity points increased the apparent duration of some saccades by as much as 20%. We did not correct for this.

There is an automatic processing feature in our program that does not require the intervention of an operator to make judgments about whether the event is a saccade or an artifact. The automatic processing feature works particularly well when a vertical EOG channel is recorded and used as an eyeblink detector. These programs were suitable for fast screening of patients but not for the formulation of a normative data base. The automatic processing feature was not used for the peak velocity–magnitude-duration parameters of this report.

The main sequence data have been plotted on both log-log coordinates and linear coordinates as Bahill[16] did previously. Linear plots allocate most of the graph space to large saccades, whereas log-log plots give space proportional to the frequency of occurrence of the saccades. The frequency of occurrence of natural saccades is a decaying exponential, with most saccades having an amplitude of 15 deg or less.[23] Thus linear plots emphasize the physiologically unusual large saccades, whereas log-log plots give more weight to normal sized saccades and make it possible to include small saccades. However, the linear plots of Fig. 3 are often more useful in clinical situations.

The data base we have described is useful not only for basic research but also for testing in the clinic. We plotted the eye movement parameters as functions of actual saccade size rather than the size of the target jumps. Our paradigm allowed us to accumulate large numbers of saccades in less than 3 min. Rather than have subjects make multiple refixations to a series of fixed targets, we randomly changed target size during the run. This helped to reduce fatigue and inattention, which often occur in recording sessions longer than 10 to 15 min. The technique is therefore well-suited for the study of patients. It is important to note, however, that a subject with data out of our normal range does not necessarily have a pathological condition. It suggests that the position and velocity waveforms of individual saccades should be studied in detail.

The standard deviations of our data are small because (1) we rejected data taken when the subjects became fatigued, as judged by a careful inspection of the eye position and eye velocity records; (2) we plotted the parameters as functions of the size of the actual saccade, not as functions of the size of the target movement; (3) we only used data from the linear range of our instrumentation; (4) the computer calculated the parameters from the velocity trace, derived with a zero-phase digital filter; and (5) we defined the size of the saccade as the size of the initial, dynamic saccade. Either the eye movements with long glissades or drifts were discarded or else the magnitude of the dynamic saccade was carefully calculated. For saccades with overshoot, the saccadic magnitude was defined to be the foot-to-peak angle, i.e., the angle between zero velocity at the start of the saccade and zero velocity at the end of the saccade. Less variability was provided by this definition for the size of the saccade than when the size of the saccade was defined as the angle between the two steady state fixation points. Saccades with dynamic overshoot were treated as two saccades: the main saccade and a small return saccade.

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REFERENCES

1. Bahill AT, Clark MR, and Stark L: The main sequence, a tool for studying human eye movements. Math. Biosciences **24**:191, 1975.
2. Bahill AT and Stark L: The trajectories of saccadic eye movements. Sci Am **240**:108, 1979.
3. Dodge R and Cline TS: The angle velocity of eye movements. Psychol Rev **8**:145, 1901.
4. Westheimer G: Mechanism of saccadic eye movements. Arch Ophthalmol **52**:710, 1954.
5. Robinson DA: The mechanics of human saccadic eye movement. J Physiol **174**:245, 1964.
6. Becker W and Fuchs AF: Further properties of the human saccadic system: eye movements and correctional saccades with and without visual fixation points. Vision Res **9**:1247, 1969.
7. Bahill AT, Bahill KA, Clark MR, and Stark L: Closely spaced saccades. Invest Ophthalmol **14**: 317, 1975.
8. Bahill AT and Stark L: Overlapping saccades and glissades are produced by fatigue in the saccadic eye movement system. Exp Neurol **48**:95, 1975.
9. Kenyon RV, Ciuffreda KJ, and Stark L: Dynamic vergence eye movements in strabismus and amblyopia: symmetric vergence. Invest Ophthalmol Vis Sci **19**:60, 1980.
10. Komatsuzaki A, Alpert J, Harris H, and Cohen B: Effects of mesencephalic reticular formation lesions on optokinetic nystagmus. Exp Neurol **34**:522, 1972.

11. Ron S, Robinson DA, and Skavenski AA: Saccades and the quick phase of nystagmus. Vision Res **12**:2015, 1972.
12. Sharpe JA, Troost BT, Dell'Osso LF, and Daroff RB: Comparative velocities of different types of fast eye movements in man. INVEST OPHTHALMOL **14**:689, 1975.
13. Shults WT, Stark L, Hoyt WF, and Ochs AL: Normal saccadic structure of voluntary nystagmus. Arch Ophthalmol **95**:1399, 1977.
14. Bahill AT, Clark MR, and Stark L: Dynamic overshoot in saccadic eye movements is caused by neurological control signal reversals. Exp Neurol **48**:107, 1975.
15. Feldon SE, Hoyt WF, and Stark L: Disordered inhibition in internuclear ophthalmoplegia, analysis of eye movement recordings with computer simulations. Brain **103**:113, 1980.
16. Bahill AT: Neurological control and the hyperfine structure of saccadic eye movements. University of California Berkeley, Doctoral Dissertation for Department of Electrical Engineering and Computer Science, 1975.
17. Boghen D, Troost BT, Daroff RB, Dell'Osso LF, and Birkett JE: Velocity characteristics of normal human saccades. INVEST OPHTHALMOL **13**:619, 1974.
18. Schmidt D, Abel LA, Dell'Osso LF, and Daroff RB: Saccadic velocity characteristics: intrinsic variability and fatigue. Aviat Space Environ Med **50**:393, 1979.
19. Baloh RW, Sills AW, Kumley WE, and Honrubia V: Quantitative measurement of saccade amplitude, duration, and velocity. Neurology **25**:1065, 1975.
20. Bahill AT, Clark MR, and Stark L: Computer simulation of overshoot in saccadic eye movements. Comput Programs Biomed **4**:230, 1975.
21. Oppenheim AV and Schafer RW: Digital Signal Processing. Englewood Cliffs, N. J., 1975, Prentice-Hall, Inc.
22. Bahill AT and Troost BT: Types of saccadic eye movements. Neurology **29**:1150, 1979.
23. Bahill AT, Adler D, and Stark L: Most naturally occurring human saccades have magnitudes of 15 degrees or less. INVEST OPHTHALMOL **14**:468, 1975.