4.2

Fast Eye Movements (Saccades): Basic Science and Clinical Correlations

B. Todd Troost, M.D.*
Louis F. Dell'Osso, Ph.D.†

I. INTRODUCTION

Fast eye movements (FEM) or saccades include voluntary and reflex saccades as well as the fast phases of various forms of nystagmus and other ocular oscillations (Table 2.1). Voluntary saccades are FEM, which are, for the most part, conjugate and function to bring objects of interest in the peripheral visual field to the fovea.

The word saccade is derived from the ancient French verb *saquer* (*sacher*), "to pull," and was used to refer to the jerk of a horse's head in response to the tug of the reins (Figure 2.1).

FEM were probably first called *saccades* by Javal[1] in referring to the quick refixational eye movements observed during reading. FEM or saccades are those classified as "eye movements of the first type" by Raymond Dodge,[2] who summarized their general characteristics as follows:

> 1. Eye movements of the first type are fundamentally reactions to eccentric retinal stimulation, and are dependent on the tendency, developed during the first month of infancy, to move the eyes so that the point of interest will be seen with the visual centre of the retina.
> 2. Their velocity is practically uninfluenced by voluntary effort. While their duration shows a slight individual variation under similar circumstances, it varies in direct proportion with the angle of movement.
> 3. They are primarily not periods of perception, but rather interruptions of vision, whose sole function is to move the line of regard to an eccentric point of interest.

The study of all eye movements, but in particular saccades, has been fruitful theoretically and clinically. The investigations of FEM exemplify the constructive interaction between clinicians and basic scientists which has given rise to the development of instrumentation, physiologic models, and quantitative definition of normal and pathologic states.

The mechanism of human saccadic eye movement was described by Robinson,[3] who proposed the idea of a separate subsystem for saccadic eye movement control.[4,5] A number of theoretical models have been proposed to explain the observed behavior of FEM; among them are those of Westheimer,[6] Young and Stark,[7] Cook and Stark,[8] Robinson,[9] Fuchs,[10] Robinson,[11] Robinson,[12] Hsu et al.[13] and Zee *et al.*[14] Dell'Osso and Daroff[15] proposed a functional organization of the ocular motor system in which two independent subsystems, version and vergence, acted synergistically (Figure 2.2). The version subsystem mediates all conjugate eye movements, and the vergence subsystem all disconjugate eye movements. Regardless of input, there are only three major categories of eye movement output: fast eye move-

* Chief, Neurology Service, Veterans Administration Hospital, and Associate Professor, Department of Neurology and Ophthalmology, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania.
† Co-director, Ocular Motor Neurophysiology Laboratory, Neurology Service, Veterans Administration Hospital and Professor, Department of Neurology, University of Miami School of Medicine, Miami, Florida.

Table 2.1
Types of FEM

FEM
Saccade
Refixation
Reflex
Voluntary
Microsaccade (Flick)
Corrective Saccade
Saccadic pursuit (Cogwheel)
Fast phase of nystagmus (Jerk)
Square wave jerk (Gegenrücke)
Macro square wave jerks
Macrosaccadic oscillations
After-image-induced
(REM) Rapid eye movement sleep saccades
Braking saccades
Opsoclonus
Voluntary nystagmus

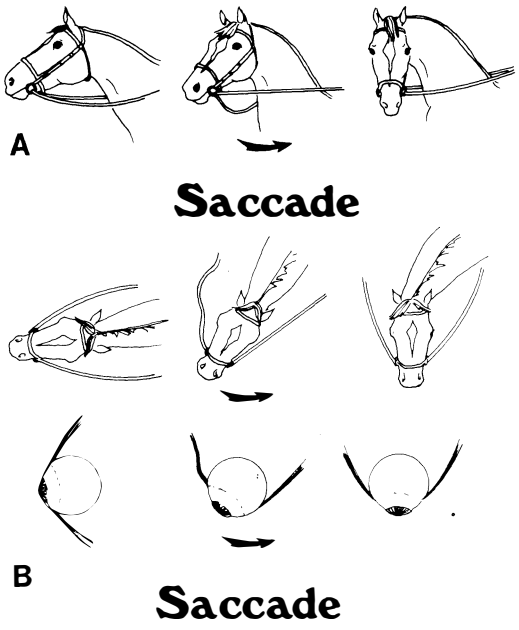

Figure 2.1. On the origins of the word *saccade*. The horse's head (eyeball) is abruptly turned (saccade) by the jerk of the reins (extraocular muscles) one taut (agonist facilitation), the other relaxed (antagonist inhibition). Final position of head or eye may then be maintained by tonic activity in the reins or extraocular muscle.

ments (FEM or saccades) and slow eye movements (SEM) from the version subsystem and vergence eye movements (VEM) from its subsystem. Within each

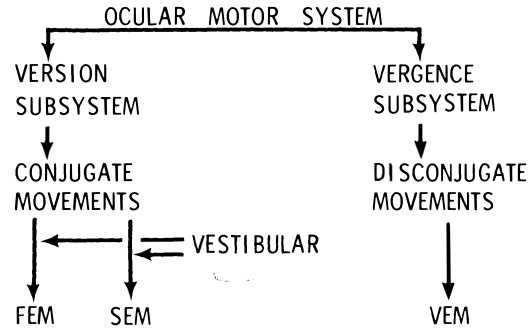

Figure 2.2. Basic organization of the ocular motor system, emphasizing the division between the vergence and dual-mode version subsystems. The three basic motor outputs are: fast eye movements (FEM), slow eye movements (SEM), and vergence eye movements (VEM). (Reprinted with permission from: R. B. Daroff and L. F. Dell'Osso.[16])

category, all eye movements are indistinguishable from all others (i.e., given an eye movement record, one cannot tell what input stimulus caused the movement). All three outputs share a common pathway from the ocular motor neurons to the extraocular muscles. The fast mode of the version subsystem mediates all conjugate saccades (FEM) and the slow mode all SEM.

The basic physiology of FEM will be reviewed briefly.

II. Physiology of FEM

The visual stimulus for FEM is target displacement. Following an instantaneous change in target position, the ocular motor system will respond with an FEM after a latency of 200–250 milliseconds. Both the peak velocity and the duration of FEM are amplitude-dependent, varying from 30–700 degrees per second and 30–100 milliseconds, respectively, for movements from 0.5–40 degrees in amplitude. FEM are conjugate and ballistic. The control system responsible for their generation is discrete (i.e., at discrete instants in time, control decisions are made based upon the continuous inflow of visual information; these decisions are essentially irrevocable). The control signal is retinal error which is reduced to 0 by the essential negative feed-

back nature of the subsystem. Figure 2.3 is a template upon which the VEM subsystem control pathways may be placed. The FEM is a closed-loop system. With head velocity 0, relative eye position (in the head) is the same as actual eye position in space; the difference in eye position and target position is the retinal error. If it is a conjugate retinal error that is sensed in the cortex, signals are sent down to the pontine paramedian reticular formation (PPRF) to initiate the eye movement to reduce this error to 0.

After the appropriate latency, an FEM response to a target displacement consists of a period of acceleration to a peak velocity and deceleration of the eyes onto the new target position. The muscular activity in the agonist-antagonist pair is characterized by a burst of maximal facilitation in the agonist and total inhibition in the antagonist during the movement. FEM deceleration is not consequent to active braking by the antagonist muscle. Rather, the two muscles merely assume the relative tensions necessary to hold the new target position. This is sufficient to accomplish the rapid deceleration because of the overdamped nature of the ocular motor plant (i.e., globe, muscles, and fatty supporting tissue).

The neural firing signal or motoneuronal controller signal necessary to achieve the rapid FEM acceleration must be a high-frequency burst of spikes which is followed by the tonic spike frequency required to stop and then hold the eyes at the new position. This combination of static and tonic firing patterns is designated the "pulse-step" of neural innerva-

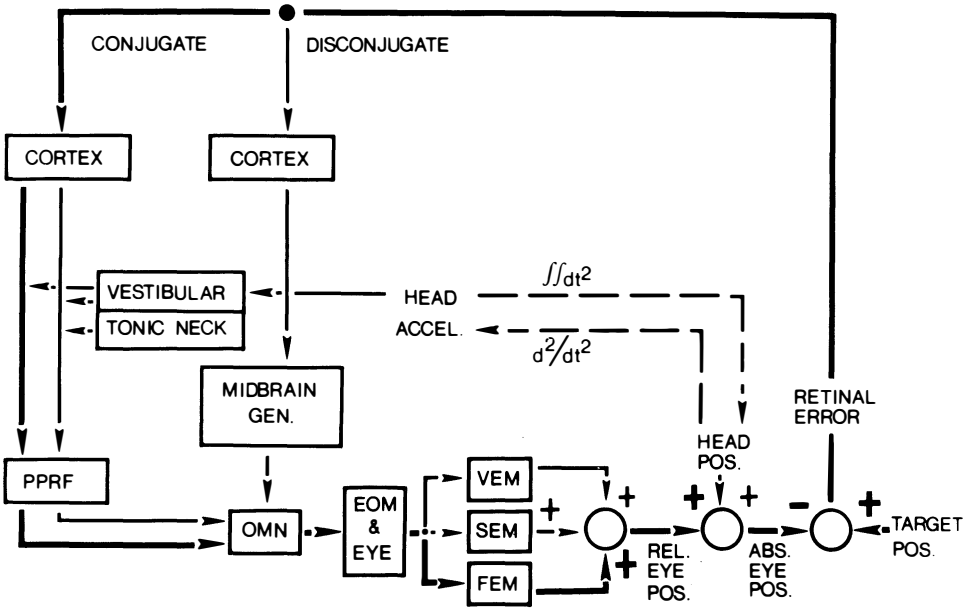

Figure 2.3. Basic closed-loop block diagram of the fast eye movement (FEM) mode of the version subsystem (*heavy lines*) superimposed on the block diagram of the total ocular motor control system. The control signal, conjugate retinal error, is sent to the cortex, and the decision to reposition the eye is forwarded to the pontine paramedian reticular formation (PPRF), where the motor commands are generated and passed on to the ocular motor nuclei (OMN). This innervation causes the extraocular muscles (EOM) to move the eye with a FEM and to change relative eye position. Assuming no change in head position, the relative position constitutes the absolute eye position which sums with target position at the retina to produce 0 retinal error. *SEM*, slow eye movement; VEM, vergence eye movement. *MIDBRAIN GEN.*, midbrain generator. The *dashed lines* show the mathematical relationships between head position and acceleration; they are *not* signal paths. (Reprinted with permission from: R. B. Daroff and L. F. Dell'Osso.[16])

tion.[12, 17–19] The relationship between the neural signals and resulting eye movements is illustrated in Figure 2.4. The eye movement in Figure 2.4 (*solid lines*) results from a step change in neural firing frequency and, reflecting the overdamped plant dynamics, is considerably slower than is a normal FEM. A normal FEM trajectory occurs only when a pulse precedes the step (*dashed lines*). A neural pulse generator and integrator combine to form the required pulse-step of innervation (Figure 2.5). The generator and integrator are both located within the PPRF at the level of the abducens nuclei.[21, 22] The location of the summing junction for the pulse and step is uncertain but may be located in the nucleus prepositus hypoglossi.[23, 24]

Knowledge of the mechanical characteristics of the eyeball, extraocular muscles and surrounding tissues (orbital plant dynamics), and the neural firing frequencies (motoneuronal controller signals) necessary to produce a saccade has allowed the development of models to study normal and abnormal FEM. This physiologic system has been modeled on both analog[25] and digital[13] computer systems. The interested reader is referred to these reports for details.

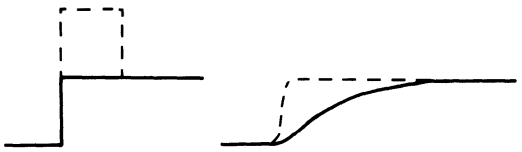

Figure 2.4. Illustration (*right*) of a slow pulseless fast eye movement (FEM) and the underlying step innervation (*left*). The *dashed lines* show the normal pulse-step of innervation and the correspondingly normal FEM. (Reprinted with permission from: R. B. Daroff and L. F. Dell'Osso.[16])

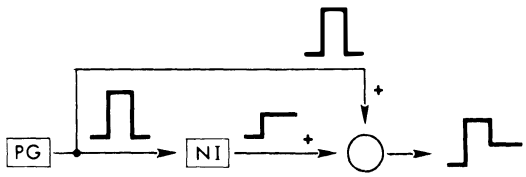

Figure 2.5. Schematic demonstrating how the pulse-step of neural innervations could be derived by summing the outputs of a neural pulse generator (*PG*) and a neural integrator (*NI*). (Reprinted with permission from: R. B. Daroff et al.[20])

III. Anatomy of Saccadic Eye Movements

We will next present a clinical formulation of the anatomic pathways believed to represent the supranuclear control of horizontal FEM. This scheme[15, 26, 27] is an operational framework which currently provides an explanation for some observed abnormalities of FEM, taking into account that critical physiologic and pathophysiologic data may be lacking. Precise details of the anatomy of horizontal eye movements are presently unavailable. What follows will be simple operational constructs not incompatible with basic anatomical studies. These are usually helpful in the correct lesion localization.

FEM have been produced by stimulation of multiple areas of the central nervous system in man and in the experimental animal. Such regions include the cerebrum (particularly area 8 of frontal cortex, known as the "frontal eye field," and the occipital cortex), cerebellum, superior colliculus, thalamus, and various brain stem sites. We depict (Figure 2.6) saccadic eye movements as originating in the contralateral cerebral hemisphere. Although area eight of Brodmann traditionally is regarded as the frontal eye field, intracellular recordings from single units have not, to date, demonstrated cortical neurons that fire before the onset of a saccade; such cells have been found within the thalamus. Saccade neurons firing as much as 150 milliseconds prior to the onset of a visually directed saccade have been identified in the inferior parietal lobule (area 7) of the monkey.[28] These neurons do not fire prior to the onset of a "spontaneous" saccade. The saccadic pathway from the contralateral cerebral hemisphere to the ipsilateral PPRF is presumably polysynaptic. This is inferred both from anatomical studies[29] and clinical observations in patients with

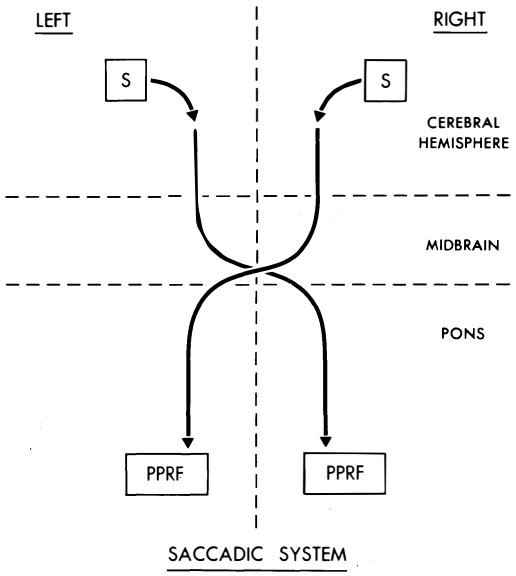

Figure 2.6. Operational schematic of saccadic anatomy. Saccades originate in contralateral cerebral hemisphere. The pathway descends through the hemisphere with multiple synapses and decussates at the midbrain-pontine junction. It then descends in the pontine paramedian reticular formation (*PPRF*) to the caudal pons at the level of the abducens nuclei. *S*, synapse. (Reprinted with permission from: R. B. Daroff and B. T. Troost.[26])

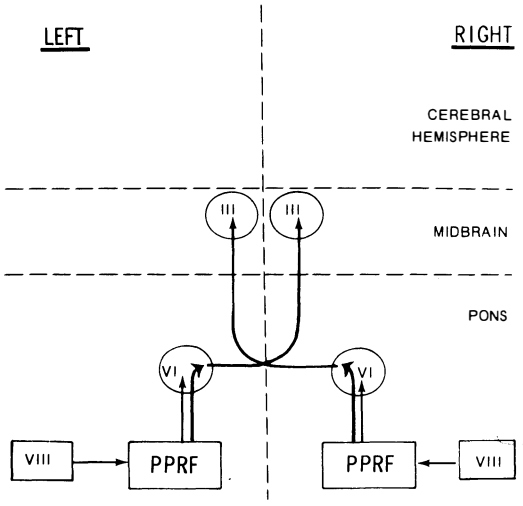

Figure 2.7. Operational schematic showing output of pontine paramedian reticular formation (*PPRF*) to ipsilateral VI and opposite III nuclei. Crossing to the latter is at level of VI, and pathway ascends to midbrain in medial longitudinal fasciculi (MLF).

progressive supranuclear palsy (PSP).[30] This condition is associated with eye movement abnormalities including saccades, yet the pathology is primarily limited to neurons within the basal ganglia and midbrain. Axons are essentially spared. In the caudal midbrain, the descending saccadic pathway undergoes a decussation and descends through the PPRF until reaching the anatomical level of the abducens nuclei. Here at the caudal one-third of the pons, the PPRF functions as a prenuclear aggregate ("pontine center") for all ipsilateral versional eye movements, including saccades. The major prenuclear structures for all horizontal versional eye movements are located within the PPRF immediately ventral to the medial longitudinal fasciculi (MLF) at the level of the abducens nuclei.[21, 22, 31-36] The PPRF generates ipsilateral horizontal eye movements via its projections to the ipsilateral abducens and, through the MLF, to the contralateral medial rectus subnucleus of the oculomotor nuclei (Figure 2.7). Recent anatomical and physiological experiments have identified additional structures which might have an important role in the mediation of eye movement. Of particular importance is the nucleus propositus hypoglosi,[23, 24] which may constitute a summing junction between the PPRF and the ocular motoneurons. There are interneurons within the abducens nuclei which project to motoneurons within the oculomotor nuclei[37, 38] (Figure 2.7). Conversely, interneurons within the oculomotor nuclei project to motoneurons in the abducens nuclei.[39] The functional significance of these latter neurons and their connections are not presently known.

An outline of supranuclear phenomenology (Table 2.2) can be supplemented with more detailed descriptions provided elsewhere.[26, 27, 31]

The cerebellum has been omitted from the diagrams, although we recognize its strong influence upon all the ocular motor subsystems.[12, 20, 31, 40-44] The role of the cerebellum in eye movements is reviewed by Zee and Robinson in the next chapter of this volume.

Table 2.2
Differential Localization of Horizontal Saccadic Palsy

Anatomic Location of Lesions	Frontomesencephalic		Pontine Paramedian Reticular Formation	
	Hemisphere	Midbrain Predecussation	PPRF Rostral to VI	PPRF Level of VI
Direction of palsy	Contralateral to lesion		Ipsilateral to lesion	
Duration of palsy with fixed lesion	Transient	Intermediate (may clear)	Permanent	
Smooth pursuit function	May be spared		Always impaired	
Conjugate deviation	Ipsilateral Invariable	Ipsilateral Variable	Contralateral only when acute	
Associated paralysis	Extremities and lower face, contralateral to lesion; ipsilateral to gaze palsy		Extremity paralysis contralateral to lesion and gaze palsy; facial paralysis ipsilateral to gaze palsy	
Cold caloric irrigation on side of palsy	Tonic ocular deviation to side of stimulus with normal fast phase in opposite direction		Tonic ocular deviation to side of stimulus with normal fast phase in opposite direction	No response
Cold caloric irrigation on side opposite palsy	Tonic deviation with variable fast phase; normal, impaired, or absent	Tonic deviation variable fast phase	Tonic deviation; occasional small amplitude fast phases	

(Reprinted with permission from: R. B. Daroff and B. T. Troost.[26]

One of the saccadic abnormalities is marked slowing during voluntary refixation attempts.[14, 45, 46] The lesion sites in such patients are probably in the brainstem rather than the cerebellum itself, as pointed out by Zee et al.,[14] as total cerebellectomy in the cat does not change the amplitude-duration characteristics of saccades but does cause inaccuracy.[43]

The terms "palsy" and "paresis" are applied to eye movement disorders in a manner analogous to that of extremity motor impairment. Thus, palsy (paralysis) implies complete disruption of the motor pathway, and paresis (weakness) implies an incomplete or subtotal disruption. However, whereas extremity strength can be graded in a simple fashion, eye movement "pareses" are considerably more complicated. At least five different clinical phenomena are regarded, perhaps loosely, as examples of saccadic paresis (Table 2.3). Each represents a specific abnormality in the neuronal fir firing pattern for FEM. The normal pattern, as described previously, consists of a pulse-step increase in firing frequency within the appropriate motoneurons (3rd, 4th, and 6th cranial nerve nuclei). There is overwhelming evidence that the pulse is generated within the PPRF and that its integration to form

Table 2.3
Operational Definitions of Supranuclear Eye Movement Disorders

I. Palsy or paralysis (*total* loss of function in a given direction beyond primary position)
  A. Saccade palsy (normal pursuit)
  B. Pursuit palsy (normal saccades; exceedingly rare)
  C. Gaze palsy (both saccades and pursuit paralyzed)
II. Paresis (incomplete or subtotal involvement)
  A. Saccade paresis (normal pursuit coexisting with any of the following:
    1. Slow saccades
    2. Gaze-paretic nystagmus
    3. Limited eccentric excursion
    4. Inability to maintain eccentrix fixation
    5. Unilateral hypometric saccades
  B. Pursuit paresis (normal saccades)
    1. Unidirectional "saccadic" pursuit
  C. Gaze paresis (combination of saccadic paresis with pursuit palsy or paresis)

(Reprinted with permission from: Daroff and Troost[25])

the step probably also occurs within the PPRF.[21, 22] Thus, the entire operation depicted in Figure 2.5 (except for the summing of the pulse and step) occurs in the PPRF at the level of the abducens nuclei.

A defective neural integrator would cause the motoneurons to receive only pulse signals. In such a situation, a saccadic refixation will be of normal speed and amplitude but, without the tonic step pattern, the eyes will not be held in the new deviated position. They will drift back toward primary position with a deceleration exponential time course. If the subject maintains an effort to refoveate the eccentric target, the slow drift will be countered by a FEM back to the target. The phasic patterning of the FEM and slow exponential drifts constitute "gaze-paretic" nystagmus (Figure 2.8).[47] This form of nystagmus thus represents a stepless eccentric saccade consequent to defective neural integration within the PPRF in a patient who maintains the gaze effort. If the latter is not maintained, the eyes would continue the decelerating exponential drift until coming to rest at primary position. This abnormality has been modeled by Abel et al.[25] and is discussed later in this volume by Daroff and Dell'Osso.

An inoperative generator is associated with complete versional paralysis in the appropriate direction. However, if the pulse is generated but blocked from summing with the step, a pulseless FEM results (Figure 2.4, *solid line*).[20, 47] The configuration of the slow pulseless FEM is in sharp contrast to the normal FEM waveform (*dashed line*). A defective generator may produce suboptimal firing frequencies which could explain limitations in amplitude excursions. Pulse-step impairments may explain the wave form of internuclear ophthalmoparesis.[48]

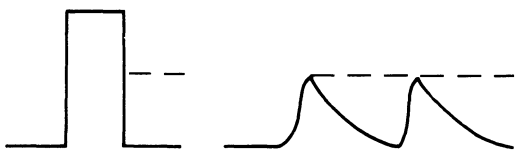

Figure 2.8. Illustration (*left*) of pulse increase of neural firing without step (*dashed lines*) and resultant eye movement (*right*). The eye makes normal eccentric fast eye movements (FEM), but absence of step causes inability to maintain deviated gaze position (*dashed lines*). The eye thus drifts back toward primary position in decelerating exponential trajectory. Stepless FEMs (saccades) are a mechanism for gaze-paretic nystagmus. (Reprinted with permission from: R. B. Daroff and L. F. Dell'Osso.[16])

IV. QUANTITATIVE STUDIES OF NORMAL FEM

A wide variety of quantitative measurements of FEM have been made in humans. Those studies performed in the Miami Ocular Motor Neurophysiology Laboratory in conjunction with Robert B. Daroff will be highlighted while reference is made to work of other investigations in the field.

The earliest studies in the Miami laboratory defined the metric characteristics of horizontal saccadic eye movements in normal humans.[49] Detailed binocular trajectory relationships during the course of voluntary refixational eye movements had been studied infrequently in normal humans. Recording from each eye simultaneously, an EOG analysis of horizontal saccades defined their metric characteristics in normal adults. Nine distinct left eye-right eye combinations were recognized and analyzed. Eye movements that were accurate were defined as normometric, those with errors, dysmetric. An inverse relationship between amplitude and accuracy emerged as the basic principle of saccadic metrics. Ten-degree saccades were normometric in the majority of trials; the remainder primarily represented conjugate under- or overshoot. However, the frequency of normometric saccades decreased significantly at 20 and 30 degrees. As the amplitude increased, conjugate undershooting became more prevalent.

Of paramount importance was the finding of dysconjugate or disjunctive eye movements. Such observations demonstrate variability and frequently only approximate equality in yoke muscle performance during horizontal saccades. The

most common difference in the performance of the two eyes resulted from a monocular error. Analysis of these errors revealed a distinct tendency toward adductor overshoot or abductor undershoot. Dysconjugate eye movements occurred in 15% of all trials, although the percentage in individual subjects varied from 2.0 to 26.2%.

All the dysmetric saccades were followed by a small corrective movement which accomplished alignment of the fovea with the new fixation target. Analysis of these corrective movements (CM) for both conjugate and dysconjugate refixational errors was reported by Weber and Daroff.[50]

Two types of CM occurred. One, designated *saccadic* CM, was fast, had a definite latency, and always followed conjugate errors. The other was slow, drift-like, without a latency; it corrected dysconjugate refixations. The term *glissadic* CM was given to the latter variety.

The saccadic correction was distinctive, easily recognized, and equal in both eyes, and it followed all binocular (conjugate) errors. The latencies from the termination of the initial movement until the onset of the corrective movements were approximately 125 milliseconds. The latency was the same with saccadic corrections for undershoots (positive CMs) and overshoots (negative CMs). The size of the CMs increased monotonically from refixations of 10 to 30 degrees.

The glissadic correction was of low velocity (approximately 30 degrees per second) and was inseparable from the terminal portion of the saccade. There was therefore no latency between the end of the initial saccade and the beginning of the correction. Thus, two distinct varieties of CMs were defined. The recognition of eye movement errors led to the proposal of an internal monitor which could modify the signal to the ocular motor nuclei and correct the monocular error. Bahill et al.[51, 52] proposed that glissades were in fact errors generated by mismatched components (that is, mismatched pulse or step components) of the neural controlling signals sent to the motor neurons. He and his coworkers identified 13 types of glissades. One type, the glissadic overshoot, is believed to be due to a pulse width error.[53]

In addition to the study of the accuracy of saccadic eye movements, various laboratories have defined normative data regarding the velocity-amplitude (amplitude and duration) characteristics of FEM. Boghen et al.[54] found considerable inter- and intrasubject variability of human saccadic velocities when refixations were made between fixed targets and recorded with standard EOG or infrared recording techniques.

Bahill et al.[55] defined what they termed the *main sequence* relationships of saccadic eye movements. These variables were saccadic magnitude or amplitude, velocity and duration (Figures 2.9 and 2.10). Baloh and associates[56, 57] have defined the saccadic velocity and duration to describe normal parameters in their laboratory. It is apparent that somewhat different standards of normalcy will be used by various laboratories in which different recording methodology, target stimulation of fast eye movement, and data analysis techniques are employed. The critical reader is referred to the individual papers cited and technical comments on recording methodology.[3, 54, 58]

As the saccade becomes larger, the peak velocity and duration become greater. The larger the saccade, the longer it takes. The peak velocity increases with increasing saccade size to a maximum velocity of 600–700 degrees per second. It is appropriate to point out that such saccades are 40 degrees plus in size and are the products of the laboratory environment. Outside the laboratory situation the head is unrestrained and usually accompanies a large eye movement. Dodge and Cline[59] noted that saccades invoked during a normal reading task were 12 degrees or less in magnitude. Noton and Stark,[60] studying normal scan paths while subjects viewed pictures, noted a sequence of saccades similar in amplitude. Bahill et al.[61] reported that most naturally occurring human saccades have a magnitude of 15 degrees or less (Figure 2.11).

Consistent with the thesis that all FEM

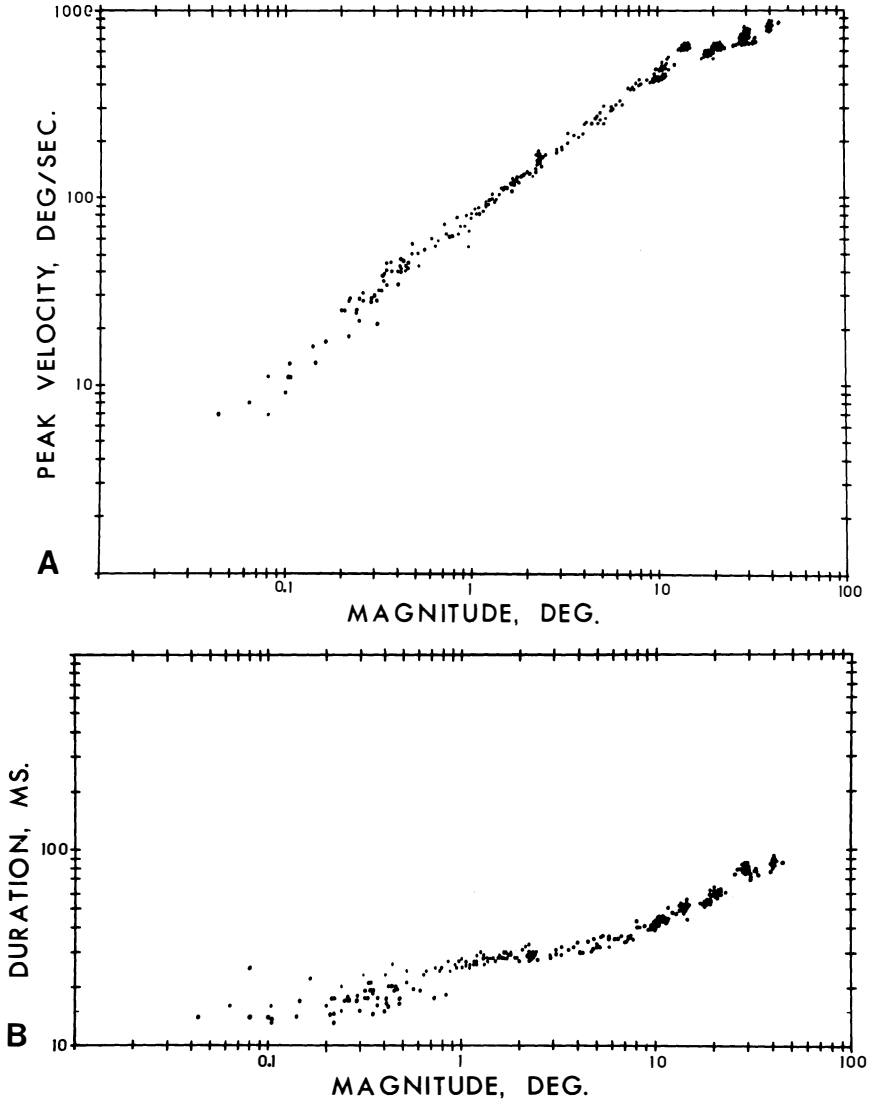

Figure 2.9. Logarithmic plots of velocity (*A*) and duration (*B*) magnitude of saccadic refixations. These are referred to as main sequence relationships by the authors. *MS*, milliseconds. (Reprinted with permission from: A. T. Bahill et al.[55])

are quantitatively similar are the results of animal[62] and human studies.[63] In the latter study, the peak velocity-amplitude characteristics of voluntary saccades and the fast phases of caloric, rotational, and optokinetic (OKN) nystagmus were compared in 10 human subjects in both light and, except for OKN, darkness. All of these FEM had similar velocities (Figure 2.12), and all slowed in darkness (Figure 2.13). The study then supported the presumption that the identical brainstem firing patterns found in monkeys[17, 21, 22] for all FEM also occur in man.

V. QUANTITATIVE STUDIES OF ABNORMAL FEM

Quantitative studies of abnormal FEM have demonstrated abnormalities at multiple central and peripheral nervous sys-

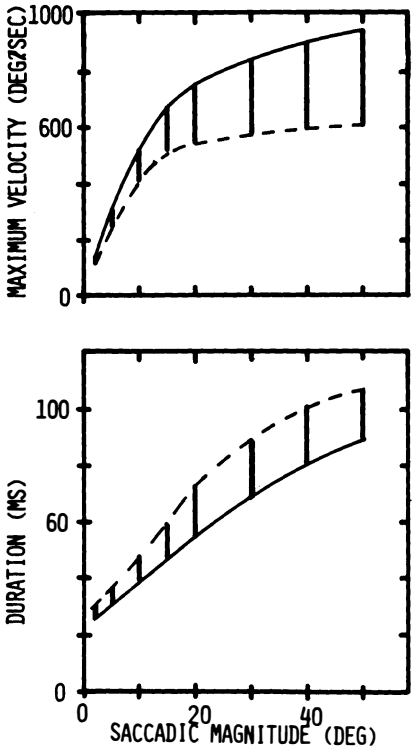

Figure 2.10. Main sequence diagrams with linear scales (based on the data of Figure 2.9, *A* and *B*). The *vertical bars* indicate the fastest and the slowest saccades for each magnitude. The *solid lines* indicate the most significant limits of the data, which are the greatest lower bound for the duration vs. magnitude and the least upper bound for the maximum velocity vs. magnitude. Each of these indicates the optimal performance of the saccadic system. For instance, the fastest possible 10-degree human saccades have points on the *solid lines* with durations of 39 milliseconds (*MS*) and maximum velocities of 520 degrees per second. Faster saccades have not been reported. However, slower saccades are common.

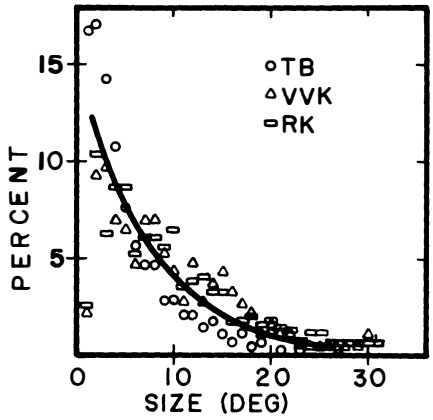

Figure 2.11. Frequency of occurrence of various-sized saccades for three normal subjects (*TB, VVK,* and *RK*). In an outdoor environment, 86% of the saccades of three subjects were 15 degrees or less in magnitude. (Reprinted with permission from: A. T. Bahill et al.[61])

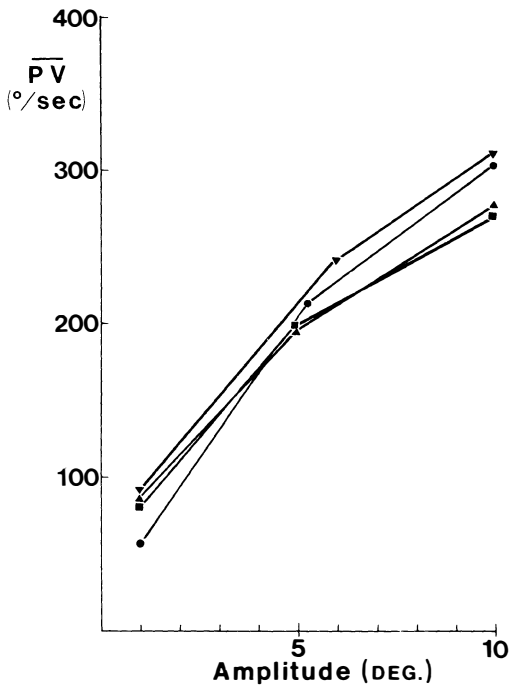

Figure 2.12. Mean peak velocity ($\overline{PV}$)-amplitude relationships for fast eye movements (FEM) in illuminated conditions. *Lines* represent least mean square fit for all data points between the indicated end points. ●, voluntary FEM; ▲, caloric fast phases; ▼, postrotary fast phases; ■, optokinetic fast phases. (Reprinted with permission from: J. A. Sharpe et al.[63])

tem levels including the neuromuscular junction and extraocular muscle in a variety of disease entities. Again the primary focus will be upon studies performed by the authors, with references to the work of other investigators.

A. Supranuclear defects of FEM

We are primarily concerned here with central supranuclear defects in which an attempt has been made quantifying the

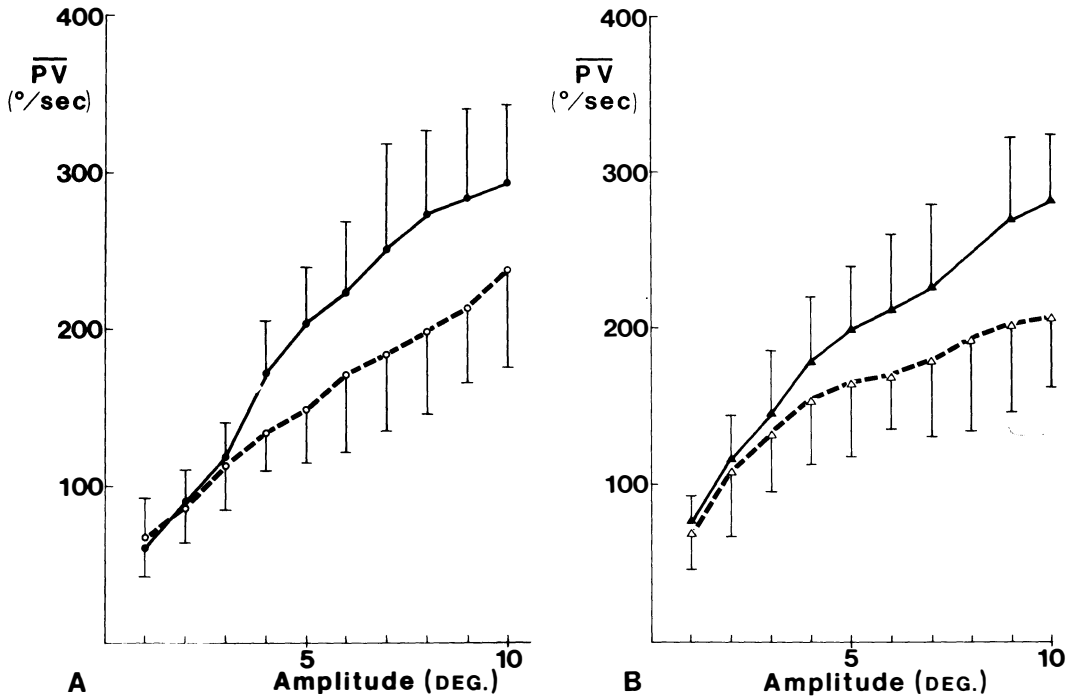

Figure 2.13. *A*, mean peak velocity ($\overline{PV}$)-amplitude relationships for fast eye movements (FEM) in light (●) and in darkness (○). *B, mean PV*-amplitude relationships for fast phases of caloric-induced nystagmus in light (▲) and in darkness (△). (Reprinted with permission from: J. A. Sharpe et al.[13])

abnormality. We previously reported a quantitative study of the refixation saccades in a man who underwent a left hemispherectomy 11 years previously.[64] The remaining right hemisphere presumably was responsible for the initiation of saccadic refixations in both directions. Normally, the right hemisphere would primarily produce FEM in a leftward direction; however, in this patient the remaining right hemisphere would make "rehabilitated" saccades in a rightward direction as well. We compared refixations in rightward and leftward directions. With the intact right hemisphere, the patient made normal leftward saccades, but on rightward gaze, saccadic function was abnormal primarily because the refixations were less accurate than normal. Normometric or "on-target" refixations occurred in only 15% of the eye movements over the amplitudes studied, as opposed to a normal average of 47%.[49] A large proportion of the leftward saccades were composed of a series of large hypometric steps[65] (Figure 2.14). There were also more frequent undershoot refixations and moncular errors than recorded in normal subjects. Study of the refixations in darkness showed the same patterns of inaccuracy and indicated that the abnormality was not entirely due to the coexisting hemianopia. According to the normative standards of the laboratory, the velocity amplitude characteristics of the saccades in both directions were normal. The results of the study of saccades in the patient with a hemispherectomy suggested that each hemisphere would have the capacity to initiate saccades of equal and normal velocity in each direction, which supported the concept of a pontine pulse generator for saccades that, when triggered, has an all-or-none type of response.[9]

Hypometric saccades (Figure 2.14) as a subtype of FEM have also been reviewed.[65]

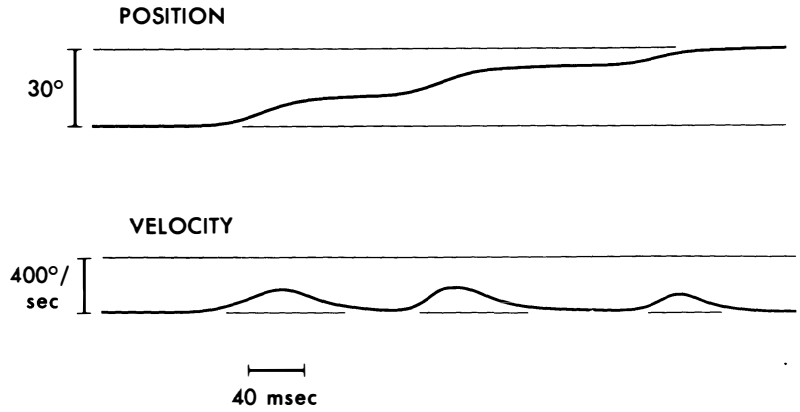

Figure 2.14. Hypometric saccade. *Upper trace,* 30-degree saccade is fragmented into three saccadic steps with short latencies between each movement. Velocity of steps depicted in *lower trace.* (Reprinted with permission from: B. T. Troost et al.[64])

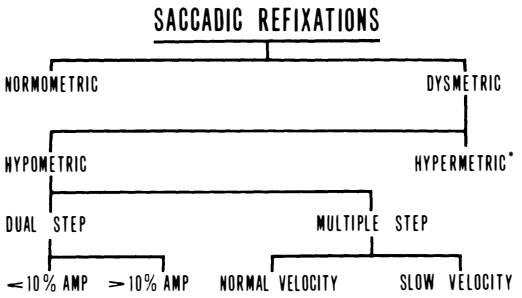

Figure 2.15. Classification of saccadic refixations. Asterisk (*) indicates that hypermetric saccades are more common in cerebellar system dysfunction and are infrequent in normal subjects. *AMP,* amplitude. (Reprinted with permission from: B. T. Troost et al.[65])

Refixations were classified according to accuracy and number of corrective movements (Figure 2.15). These refixations with more than a single CM for an undershoot error were classified as multiple-step hypometric saccades (MSHS). We consider MSHS pathologic only if the individual segments had pathologically slow velocity or prolonged duration as in PSP,[30, 66] or if, despite normal velocity segments, they comprise a major proportion of the refixations. The latter finding was present in the rightward refixations of the hemispherectomy patient.[64]

Saccadic palsy with normal-pursuit eye movements occurs in both congenital and acquired ocular motor apraxia, presumably due to a bilateral abnormality in the frontomesencephalic projections to the brainstem. A patient with ocular motor apraxia does not have normal FEM but instead has head movements to a larger degree than normal.[67–69] Defective FEM have been studied in a variety of neurologic disorders which primarily affect the subcortical gray matter and, in particular, the basal ganglia. Slow eye movements have been recorded in Huntington's chorea[70, 71] and Wilson's disease.[72] Hypometric saccades and prolonged latency between refixation have been described in Parkinson's disease.[73, 74]

PSP is a neurologic disorder characterized by axial rigidity, dementia, and a progressive defect in voluntary eye movements.[75] While clinical descriptions of the condition date back over 70 years,[76] no systematic analysis of the eye movement disturbance had been performed until recently. We studied the ocular motor deficits in eight patients with PSP.[30] Some of the patients had total paralysis of vertical eye movements, but none had completely lost the ability to perform horizontal eye movements. All patients had a defect in ocular fixation previously undescribed in this condition: the universal presence of square wave jerks (SWJ) (Figure 2.16). Analysis of refixation saccades demonstrated hypometria (Figure 2.17, *A* and *B*), slow velocity-amplitude relationships (Figure 2.18), and profound prolongation of

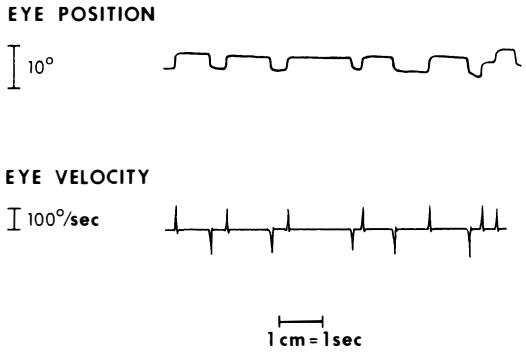

Figure 2.16. Square wave jerks or Gegenrücke observed during fixation attempt in a patient with progressive supranuclear palsy. (Reprinted with permission from: B. T. Troost and R. B. Daroff.[30])

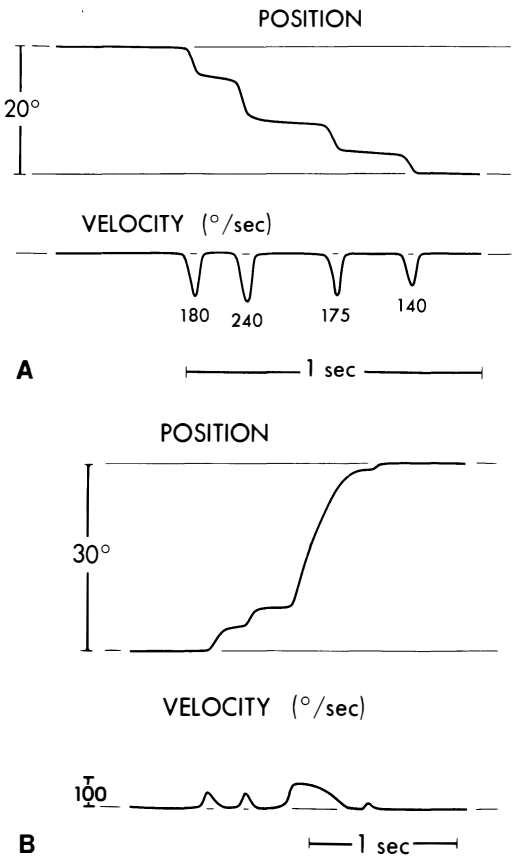

Figure 2.17. *A*, hypometric saccade with normal velocity segments contrasted with hypometric saccade with slow segments (*B*) in patient with progressive supranuclear palsy. (Reprinted with permission from: B. T. Troost and R. B. Daroff.[65])

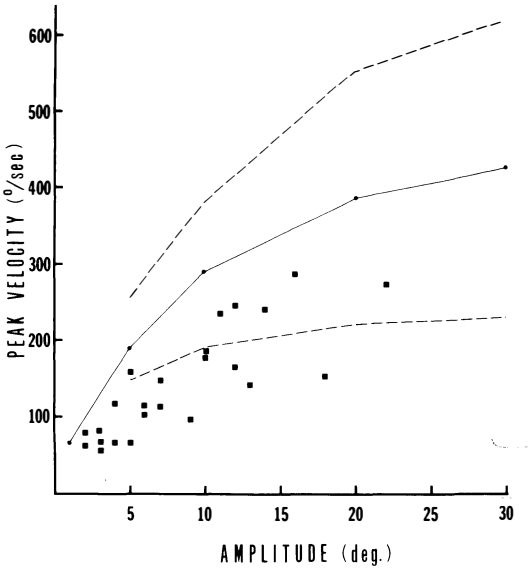

Figure 2.18. Velocity (degrees per second)-amplitude plot of individual saccadic refixations in patient with progressive supranuclear palsy (PSP). Normative data with ± standard durations from Boghen et al.[54] (Reprinted with permission from: B. T. Troost and R. B. Daroff.[30])

duration (Figure 2.19). Different defective motoneuronal pulse configurations were postulated which could produce the observed saccadic abnormalities (Figure 2.20).

B. Internuclear Defects of FEM

Monocular slowing of adduction in a partially developed internuclear ophthalmoplegia has been recorded in several publications.[79–83] In internuclear ophthalmoplegia, the adducting eye either fails to adduct or does so slowly. The abducting eye develops nystagmus with the fast phase in the direction of gaze; the initial abduction saccade is of normal velocity. The slowness of adduction (which at times may be quite subtle) is accentuated during optokinetic testing.[84] If, for example, the patient has a left internuclear ophthamoplegia, the left eye will be slow in adduction when gaze is directed to the right. The right eye (the abducting eye) has normal fast phases, but the left (abducting eye) is slow, this difference being clinically more apparent during the OKN test. An expla-

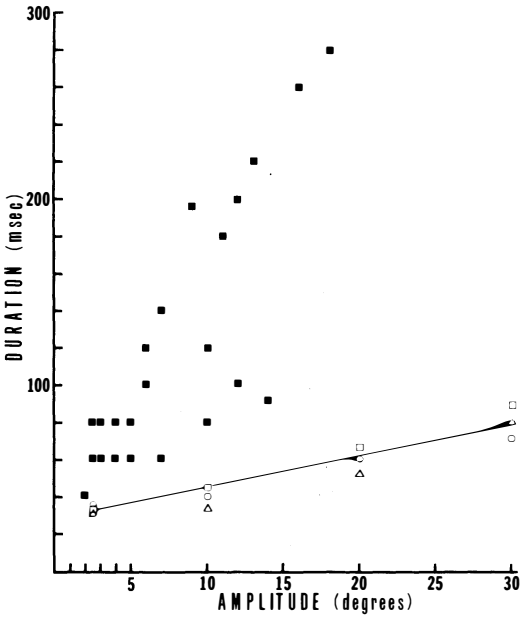

Figure 2.19. Duration-amplitude plot of individual saccadic refixations in patient with PSP (■). Normative data shown in *lower line* is from Dodge and Cline[59] (○), Cook et al.[77] (△), and Bahill and Stark[55] (□). (Reprinted with permission from B. T. Troost and R. B. Daroff.[30])

nation of the abduction nystagmus in internuclear ophthalmoplegia based on direct recordings from the medial longitudinal fasciculus in monkeys has been made by Pola and Robinson.[85]

C. Infranuclear Defects of FEM

Partial peripheral lesions of the 3rd, 4th, and 6th cranial nerves have produced expected saccadic slowing with gaze in the direction of the paralytic lateral rectus.[86–88] However, central nervous system adaptation for paralytic deficits involving 3rd- and 6th-nerve function has also been postulated to explain abnormal saccadic function when gaze is directed away from the paralytic muscle.[47, 87, 89] An initial saccade away from a paralytic muscle is generated primarily by excitation of the agonist independent of initial eye position.[90] However, maintenance of position may not be held by the paretic eye as the tonic firing level is coded for the position of the nonparetic eye and drifting in the direction of the weak muscles occurs.[89]

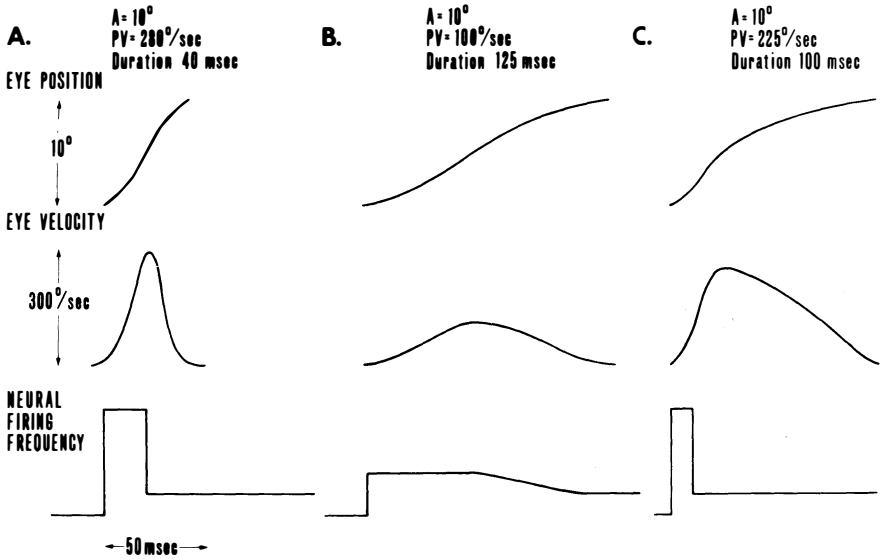

Figure 2.20. Theoretic configurations of eye position, eye velocity, and neural firing frequency plots producing normal (*A*) and abnormal (*B* and *C*) saccades, based on data in patients with progressive supranuclear palsy (PSP). *A*, Normal 10-degree saccade, with peak velocity 280 degrees per second, and duration of 40 milliseconds. Normal "pulse-step" neural firing frequency shown. *B*, slow 10-degree saccade (peak velocity, 100 degrees per second; duration, 125 milliseconds). Defective pulse, virtually "pulseless." *C*, long duration 10-degree saccade with peak velocity near normal 225 degrees per second, pulse unsustained. *A*, amplitude; *PV*, peak velocity. (Reprinted with permission from: B. T. Troost and R. B. Daroff.[30])

D. Muscular Defects of FEM

In extraocular muscle disease, the major saccadic abnormality is that of decreased velocity. Saccadic velocity measurements are reportedly useful during and after strabismus surgery.[91-93] In myasthenia gravis the velocity of FEM may be slowed and may increase following intravenous edrophonium chloride.[94-96] Increased velocity of the fast phase of OKN has been useful in establishing or confirming the diagnosis of ocular myasthenia gravis.[97, 98] Isolated medial rectus involvement may produce adduction failure or slowing and may mimic internuclear ophthalmoplegia in myasthenia gravis.[99, 100]

Rapid eye movements have also been reported in myasthenia gravis, giving rise to theories of differential muscle fiber involvement or central nervous system adaptation.[101, 102]

E. Saccadic Subsystem Oscillatory Defects

FEM instabilities may be included among the ocular oscillations which also include a variety of types of nystagmus reviewed in more detail in this symposium by Daroff and Dell'Osso. Those oscillations which are for the most part entirely composed of FEM include opsoclonus,[27] ocular dysmetria,[102] macrosaccadic oscillations,[103] voluntary nystagmus,[104] and macro square wave jerks.[78] Study of the last type of oscillation exemplifies the manner in which quantitative eye movement recordings may provide information confirming clinical diagnosis and stimulate theoretic considerations of ocular motor control. Macro square wave jerks were observed in a woman with demyelinating disease whose eye movement recordings also document a bilateral internuclear ophthalmoplegia. Figure 2.21 illustrates an initial off-target saccade to the left followed after a latency of approximately 80 milliseconds by a return saccade to the right when she maintains fixation momentarily on target. The fixation is then followed by a saccadic oscillation away from target again to the left. These are macro square wave jerks (MSWJ); the fact that they are not perfectly rectangular is due to bilateral internuclear ophthalmoplegia (INO). The abducting saccades have higher velocity peaks than do adducting saccades, with both eyes abducting faster than adducting. This instability is, then, an instability of the FEM or saccadic subsystem such that there is a spurious saccade, moving the eyes from fixation (to the left), followed by rapid corrective saccades to the right. Because the MSWJ occurred in darkness, retinal error signals did not generate the corrective saccade. Since the patient had bilateral INO, the abducting eye was further from fixation than was the slow adducting eye, after leaving the target, and therefore eye position information could not be utilized to program a conjugate return saccade to target. These considerations led to the proposal of a model to explain the corrective FEM phase (Figure

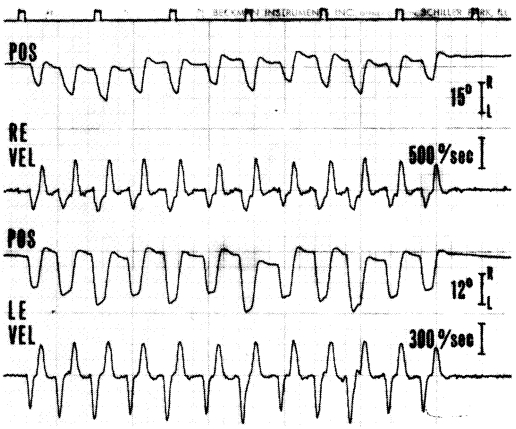

Figure 2.21. Binocular position (*POS*) and velocity (*VEL*) recordings of macro square wave jerks showing their unidirectional nature relative to the intended gaze position evident at the beginning and end of the *POS* traces. The oscillation consists of a leftward saccade that moves the eyes off the target and is followed, after a variable but brief latency, by a corrective rightward saccade which results in refoveation. The patient's bilateral internuclear ophthalmoparesis, with the right eye (*RE*) more affected than the left eye (*LE*), is apparent in both the *POS* and *VEL* wave forms. Different calibration for the two eyes should be noted. The timing marks at the top indicate 1-second intervals. *R*, right; *L*, left. (Reprinted with permission from: L. F. Dell'Osso et al.[78])

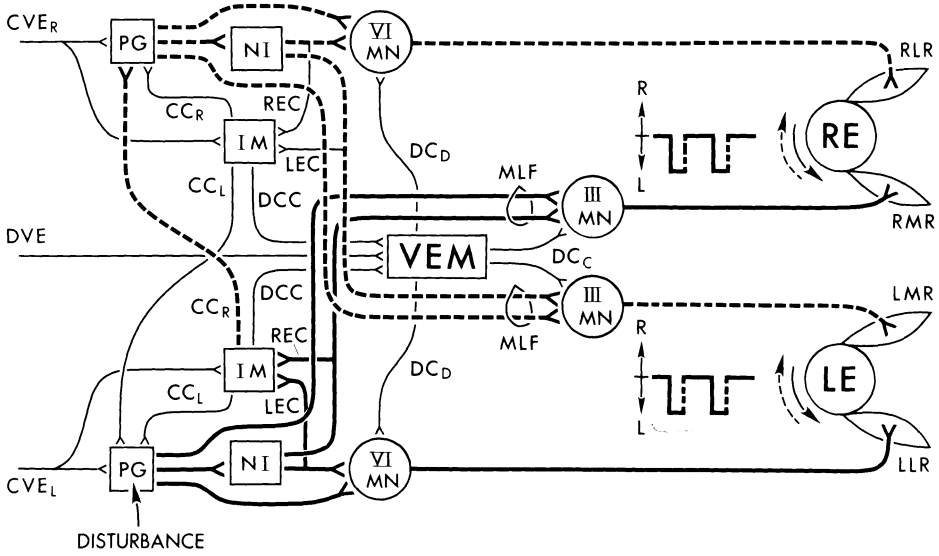

Figure 2.22. Binocular model of brain stem output portions of the horizontal fast eye movement and vergence eye movement (*VEM*) subsystems illustrating the functional operation of an internal monitor (*IM*) in the generation of corrective eye movements. Conjugate visual errors to the right and left (CVE_R and CVE_L, respectively) drive the pulse generators (*PG*) on their respective side to produce saccades.

The output of the *PG* is integrated in the neural integrator (*NI*), and the resulting step of innervation is summed with the original pulse from the pulse generator at the motoneuron (*MN*). (Motoneuronal summing is provided for simplicity only; summing may actually occur at a prenuclear level). Signals then go to the respective extraocular muscles (*RLR, RMR, LMR, LLR*) to drive the right (*RE*) and the left (*LE*) eyes. Disconjugate visual errors (*DVE*) drive the VEM subsystem to produce disconjugate commands of convergence (DC_C) and divergence (DC_D). The *IM* monitors the commands to both eyes (*REC* and *LEC*), compares them with the desired output (*CVE*), and directs the required conjugate correction to the right (CC_R) or left (CC_L) PG as well as any required disconjugate corrective command (*DCC*) to the VEM subsystem. The disturbance input for this patient and the pathways for the consequent abnormal leftward saccade are in *heavy solid lines,* with the pathways for the corrective rightward saccade in *dashed lines.* The resulting macro square wave jerks are shown next to each eye. For simplicity, we have not diagrammed the internuclear ophthalmoparesis. (Reprinted with permission from: L. F. Dell'Osso et al.[78])

2.22). We postulated a disturbance in the right pontine paramedian reticular formation (PPRF) pulse generator which would produce the leftward away-from-target saccade in both eyes. The leftward saccade command is sensed by an internal monitor copying the position command signal destined for the individual ocular motor nuclei and comparing the signal with the ideal or "desired" fixation position (usually based on retinal information). After the spurious saccade, an error is delected, sent across to the opposite side of the pons to the rightward pulse generator and, with a very short latency, the corrective saccade (*in dashed lines*) gets the eyes back to the target.

In summary, we have briefly reviewed some of the clinical and theoretical information concerning saccades or FEM. This review is not inclusive and has concentrated primarily upon our personal studies.

REFERENCES

1. Javal, E. Essai sur la physiologie de la lecture. *Ann. Ocul., 82:* 242–253, 1879.
2. Dodge, R. Five types of eye movement in the horizontal meridian plane of the field of regard. *Am. J. Physiol., 8:* 207–329, 1903.

3. Robinson, D. A. The mechanics of human saccadic eye movement. *J. Physiol. (Lond.), 174:* 245–264, 1964.
4. Robinson, D. The oculomotor control system: a review. *Proc. IEEE Trans. Biomed. Eng., 56:* 1032–1049, 1968.
5. Robinson, D. A. Eye movement control in primates. *Science, 161:* 1219–1224, 1968.
6. Westheimer, G. Mechanism of saccadic eye movement. *Arch. Ophthalmol. 52:* 710–723, 1954.
7. Young, L. R., Stark, L. Variable feedback experiments testing a sampled data model for eye tracking movements. *IEEE Trans. Human Factors Electronics, 4:* 38–51, 1963.
8. Cook, G., and Stark, L. The human eye-movement mechanism: experiments, modeling and model testing. *Arch. Ophthalmol., 79:* 428–436, 1968.
9. Robinson, D. A. Models of oculomotor neural organization, In *The Control of Eye Movements,* edited by P. Bach-y-Rita, C. C. Collins, and J. E. Hyde, pp. 519–538. New York, Academic Press, 1971.
10. Fuchs, A. F. The saccadic system. In *The Control of Eye Movements,* edited by Bach-y-Rita, C. C. Collins, and J. E. Hyde, pp. 343–362. New York, Academic Press, 1971.
11. Robinson, D. A. Models of the saccadic eye movement control system. *Kybernetik, 14:* 71–84, 1973.
12. Robinson, D. A. Oculomotor control signals. In *Basic Mechanisms of Ocular Motility and Their Clinical Implications,* edited by G. Lennerstrand and P. Bach-y-Rita, pp.337–374. New York, Pergamon Press, 1975.
13. Hsu, F. K., Bahill, A. T., and Stark L. Parametric sensitivity analysis of a homeomorphic model for saccadic and vergence eye movements. *Comput. Programs Biomed., 6:* 108–116, 1976.
14. Zee, D. S., Optican, L. M., Cook, J. D., Robinson, D. A., and Engle W. K. Slow saccades in spinocerebellar degeneration. *Arch. Neurol., 33:* 243–251, 1976.
15. Dell'Osso, L. F., and Daroff, R. B. Functional organization of the ocular motor system. *Aerosp. Med., 45:* 873–875, 1974.
16. Daroff, R. B., and Dell'Osso, L. F. The control of eye movements. In *Neurological Reviews, 1976,* chap. 7, pp. 143–170. American Academy of Neurology, Minneapolis, 1976.
17. Robinson, D. A. Oculomotor unit behavior in the monkey. *J. Neurophysiol., 33:* 393–404, 1970.
18. Fuchs, A. F., and Luschei, Firing patterns of abducens neurons of alert monkeys in relationship to horizontal eye movement. *J. Neurophysiol, 33:* 382–392, 1970.
19. Robinson, D. A., and Keller E. L. The behavior of eye movement motoneurons in the alert monkey. *Bibl. Ophthalmol., 82:* 7–16, 1972.
20. Daroff, R. B. Concluding remarks: summary of clinical presentations. In *Basic Mechanisms of Ocular Motility and Their Clinical Implications,* edited by G. Lennerstrand and P. Bach-y-Rita, pp. 435–443. Pergamon Press, New York, 1975.
21. Keller, E. L. Participation of medial pontine reticular formation in eye movement generation in monkey. *J. Neurophysiol., 37:* 316–332, 1974.
22. Keller, E. L. The role of the brainstem reticular formation in eye movement control. In *Eye Movements,* edited by B. A. Brooks and F. J. Bajandas, ARVO Symposium 1976, Plenum Press, New York, 1977. pp. 105–126.
23. Graybiel, A. M., and Hartwieg, E. A. Some afferent connections of the oculomotor complex in the cat: an experimental study with tracer techniques. *Brain Res., 81:* 543–551, 1974.
24. Baker, R. The nucleus prepositus hypoglossi. In *Eye Movements,* edited by B. A. Brooks and F. J. Bajandas, ARVO Symposium 1976, pp. 145–178. Plenum Press, New York, 1977.
25. Abel, L., Dell'Osso, L. F., and Daroff, R. B. Analog model for gaze-evoked nystagmus. *Proc. IEEE Trans. Biomed. Eng., 25:* 71–75, 1978.
26. Daroff, R. B., and Troost, B. T. Supranuclear disorders of eye movements. In *Clinical Ophthalmology* edited by T. D. Duane, Harper & Row, Hagerstown, Md., 1976. vol. 2, chap. 10.
27. Daroff, R. B., and Troost, B. T. Supranuclear disorders of eye movements. In *Neuro-Ophthalmology,* edited by J. S. Glaser, Harper & Row, Hagerstown, Md., 1978.
28. Lynch, J. C., Mountcastle, V. B., Talbot, W. H., and Yin, T. C. T. Parietal lobe mechanisms for directed visual attention. *J. Neurophysiol., 40:* 362–389, 1977.
29. Astruc, J. Corticofugal connections of area 8 (frontal eye field) in *Macaca mulatta. Brain Res., 33:* 241–256, 1971.
30. Troost, B. T., and Daroff, R. B. The ocular motor defects in progressive supranuclear palsy (PSP). *Ann. Neurol., 2:* 397–403, 1977.
31. Daroff, R. B., and Hoyt, W. F. Supranuclear disorders of ocular control systems in man. Clinical, anatomical and physiological correlations, 1969. In *The Control of Eye Movements,* edited by P. Bach-y-Rita, C. C. Collins, J. E. Hyde, pp. 175–235. New York, Academic Press, 1971.
32. Goebel, H. H., Komatsuzaki, A., Bender, M. B., and Cohen, B. Lesions of the pontine tegmentum and conjugate gaze paralysis. *Arch. Neurol., 24:* 431–440, 1971.
33. Cohen, B., and Henn, V. Unit activity in the pontine reticular formation associated with eye movements. *Brain Res., 46:* 403–410, 1972.
34. Cohen, B., and Henn, V. The origin of quick phases of nystagmus in the horizontal plane. *Bibl. Ophthalmol., 82:* 36–55, 1972.
35. Cohen, B., and Komatsuzaki, A. Eye movements

produced by stimulation of the pontine reticular formation: evidence for integration in the oculomotor pathways. *Exp. Neurol., 36:* 101–117, 1972.

36. Highstein, S. M., Cohen, B., and Matsunami K. Monosynaptic projections from the pontine reticular formation to the IIIrd nucleus in the cat. *Brain Res., 75:* 340–344, 1974.
37. Baker, R., and Highstein, S. M. Physiological identification of interneurons and motoneurons in the abducens nucleus. *Brain Res., 91:* 292–298, 1975.
38. Highstein, S. M. Abducens to medial rectus pathway in the MLF: A possible cellular basis for the syndrome of internuclear ophthalmoplegia. In *Eye Movements,* edited by B. A. Barnes and F. A. Bajandas pp. 127–144. ARVO Symposium 1976, Plenum Press, New York, 1977.
39. Maciewicz, R. J. Kaneko, C. R. S., Highstein, S. M., and Baker R. Morphological identification of interneurons in the oculomotor nucleus that project to the abducens nucleus in the cat. *Brain Res., 96:* 60–65, 1975.
40. Daroff, R. B. Ocular motor manifestations of brainstem and cerebellar dysfunction. In *Neuro-Ophthalmology,* edited by J. L. Smith, vol. V, pp. 104–119. Huffman, Hallandale, Florida, 1970.
41. Robinson, D. A. The neural basis for pontine and cerebellar control of eye movement. Jap. J. Ophthalmol., *19:* 25–38, 1975.
42. Robinson, D. A. How the oculomotor system repairs itself. *Invest. Ophthalmol., 14:* 413–415, 1975.
43. Westheimer, G., and Blair S. M. Oculomotor defects in cerebellectomized monkeys. *Invest. Ophthalmol., 12:* 618–621, 1973.
44. Hoyt, W. F., and Frisén, L. Supranuclear ocular motor control. Some clinical considerations—1974. In Basic Mechanisms of Ocular Motility and Their Clinical Implications, edited by G. Lennerstrand and P. Bach-y-Rita, pp. 379–392. Pergamon Press, New York, 1975.
45. Wadia N. H., and Swami R. K. A new form of heredo-familial spinocerebellar degeneration with slow eye movements. *Brain, 94:* 359–374, 1971.
46. Zee, D. S., Yee, R. D., Cogan, D. G., Robinson, D. A., and Engel, W. K. Ocular motor abnormalities in hereditary cerebellar ataxia. *Brain, 99:* 207–234, 1976.
47. Kommerell, G. Clinical clues for the organization of horizontal quick eye movements and subsequent periods of fixation. In *Basic Mechanisms of Ocular Motility and the Clinical Implications,* edited by G. Lennerstrand, P. Bach-y-Rita, pp. 325–335. Pergamon Press, New York, 1975.
48. Dell'Osso, L. F., Robinson, D. A., and Daroff R. B. Optokinetic asymmetry and internuclear ophthalmoplegia. *Arch. Neurol., 31:* 138–139, 1974.
49. Weber, R. B., and Daroff R. B. The metrics of horizontal saccadic eye movements in normal humans. *Vision Res., 11:* 921–928, 1971.
50. Weber R. B., and Daroff, R. B. Corrective movements following refixation saccades: type and control system analysis. *Vision Res., 12:* 467–475, 1972.
51. Bahill, A. T., and Stark, L. Overlapping saccades and glissades are produced by fatigue in the saccadic eye movement system. *Exp. Neurol., 481:* 95–106, 1975.
52. Bahill, A. T., Clark, M. R., and Stark, L. Glissades—Eye movements generated by mismatched components of the motoneuronal control signal. *Math Biosci., 26:* 319–323, 1975.
53. Bahill, A. T., Hsu, F., and Stark, L. Glissadic overshoots are due to pulse width errors. *Arch. Neurol. 35:* 138–142, 1978.
54. Boghen, D., Troost, B. T., Daroff, R. B., et al. Velocity characteristics of normal human saccades. *Invest. Ophthalmol., 13:* 619–623, 1974.
55. Bahill, A. T., Clark, M. R., and Stark, L. The main sequence, a tool for studying human eye movements. *Math Biosci., 24:* 191–204, 1975.
56. Baloh, R. W., Sills, A. W., Kumley, W. E., et al. Quantitative measurement of saccade amplitude, duration and velocity. *Neurology, 25:* 1065–1070, 1975.
57. Baloh, R. W., Konrad, H. R., and Sills, A. W., et al. The saccade velocity test. *Neurology, 25:* 1071–1076, 1975.
58. Troost, B. T., Daroff, R. B., and De-l'Osso, L. F. Eye tracking patterns in schizophrenia. *Science, 184:* 1202–1203, 1974.
59. Dodge, R., and Cline, T. The angle velocity of eye movements. *Psychol. Rev., 8:* 125–157, 1901.
60. Noton, D., and Stark, L. Scan paths in saccadic eye movements while viewing and recognizing patterns. *Vision Res., 11:* 929–942, 1971.
61. Bahill, A. T., Adler, D., and Stark, L. Most naturally occurring human saccades have magnitudes of 15 degrees or less. *Invest. Ophthalmol., 14:* 468–469, 1975.
62. Ron, S., Robinson, D. A., and Skavenski, A. A. Saccades and the quick phase of nystagmus. *Vision Res., 12:* 2015–2020, 1972.
63. Sharpe, J. A., Troost, B. T., Dell'Osso, L. F., and Daroff, R. B. Comparative velocities of different types of fast eye movements in man. *Invest. Ophthalmol., 14:* 689–692, 1975.
64. Troost, B. T., Weber, R. B., and Daroff, R. B. Hemispheric control of eye movements. I. Quantitative analysis of refixation saccades in a hemispherectomy patient. *Arch Neurol., 27:* 441–448, 1972.
65. Troost, B. T., Weber, R. B., Daroff, R. B. Hypometric saccades. *Am. J. Ophthalmol., 78:* 1002–1005, 1974.
66. Troost, B. T., Daroff, R. B., and Dell'Osso, L. F.

Quantitative analysis of the ocular motor deficit in progressive supranuclear palsy (PSP). *Trans. Am. Neurol. Assoc., 101:* 60–64, 1976.
67. Cogan, D. G. A type of congenital ocular motor apraxia presenting jerky eye movements. *Am. J. Ophthalmol., 36:* 433–441, 1953.
68. Zee, D. S., Yee, R. D., and Singer, H. S. Congenital ocular motor apraxia. Eye-head coordination, *Brain, 100:* 581–599, 1977.
69. Zee, D. S. Disorders of eye-head coordination. In *Eye Movements,* edited by B. A. Brooks and F. J. Bajandas, ARVO Symposium 1976, pp. 9–39. New York, Plenum Press, 1977.
70. Starr, A. A. A disorder of rapid eye movements in Huntington's chorea. *Brain, 90:* 545–564, 1967.
71. Eisner, L., Troost, B. T., and Daroff, R. B. Eye movements in Huntington's chorea (unpublished observations).
72. Kirkham, T. H., and Kamin, D. F. Slow saccadic eye movements in Wilson's disease. *J. Neurol. Neurosurg. Psychiatry, 37:* 191–194, 1974.
73. DeJong, J. D., and Jones, G. M. Dynamic characteristics of saccadic eye movements in Parkinson's disease. *Exp. Neurol., 31:* 17–31, 1971.
74. DeJong, J. D., and Jones, G. M. Akinesia, hypokinesia and bradykinesia in the oculomotor system of patients with Parkinson's disease. *Exp. Neurol., 32:* 58–68, 1971.
75. Steele, J. C., Richardson, J. C., and Olszewski, J. Progressive supranuclear palsy: A heterogenous degeneration involving brainstem, basal ganglia and cerebellum with vertical gaze and pseudobulbar palsy, nuchal dystonia and dementia. *Arch. Neurol., 10:* 333–359, 1964.
76. Posey, W. C. Paralysis of the upward movements of the eyes. *Ann. Ophthalmol., 13:* 523–529, 1904.
77. Cook, G., Stark, L., Zuber, B. L. Horizontal eye movements studied with the on line computer. *Arch. Ophthalmol., 76:* 589–595, 1966.
78. Dell'Osso, L. F., Troost, B. T., and Daroff, R. B. Macro square wave jerks. *Neurology, 25:* 975–979, 1975.
79. Kommerell, G. Die internukleare ophthalmoplegie. Nystagmographische analyse. *Monatsb. augenheilk., 158:* 349–358, 1971.
80. Fricker, S. J., and Sanders, J. J. Internuclear ophthalmoplegia and associated abnormalities in eye motion timing (differential delays). *Neurology, 25:* 281–285, 1975.
81. Metz, H. S. Saccadic velocity measurements in internuclear ophthalmoplegia. *Am. J. Ophthalmol., 81:* 296–299, 1976.
82. Mastaglia, F. L., and Black, J. L. Saccadic velocities in multiple sclerosis. *Lancet,* 1359, 1976.
83. Bird, A. C., and Leech, J. Internuclear ophthalmoplegia. *Br. J. Ophthalmol., 60:* 645–651, 1976.
84. Smith, J. L., and David, N. J. Internuclear ophthalmoplegia. Two new clinical signs. *Neurology, 14:* 307–309, 1964.
85. Pola, J., and Robinson, D. A. An explanation of eye movements seen in internuclear ophthalmoplegia. *Arch. Neurol., 33:* 447–452, 1976.
86. Metz, H. S., Scott, A. B., O'Meara, D., et al. Ocular saccades in lateral rectus palsy. *Arch. Ophthalmol., 84:* 453–460, 1970.
87. Theopold, H., and Kommerell, G. Phasische und tonische Funktion der Augenmuskeln. Untersuchungen an Patienten mit Oculomotorius- oder Abducens—Paralyse. *Albrecht v. Graefes Arch Klin. Exp. Ophthalmol., 192:* 247–254, 1974.
88. Rosenbaum, A. L., Carlson, M. R., and Gaffney, R. Vertical saccadic velocity determination in superior oblique palsy. *Arch. Ophthalmol., 95:* 821–823, 1977.
89. Zee, D. S., and Yee, R. D. Abnormal saccades in paralytic strabismus. *Am. J. Ophthalmol., 83:* 112–114, 1977.
90. Collins, C. C. The human ocular motor control system. In *Basic Mechanisms of Ocular Motility and Their Clinical Implications,* edited by G. Lennerstrand and P. Bach-y-Rita, pp. 145–180, Pergamon Press, New York, 1975.
91. Metz, H. S., and Rice, L. S. Human eye movements following horizontal rectus muscle disinsertion. *Arch. Ophthalmol., 90:* 265–267, 1973.
92. Metz, H. S., and Jampolsky, A. Change in saccadic velocity following rectus muscle transposition. *J. Pediatr. Ophthalmol., 11:* 129–134, 1974.
93. Rosenbaum, A. L., and Metz, H. S. Diagnosis of lost or slipped muscle by saccadic velocity measurements. *Am. J. Ophthalmol., 77:* 215–222, 1974.
94. Manz, F., and Schmidt, D. The diagnosis of ocular myasthenia in childhood. *Klin. Monatsbl. Augenheilkd., 157:* 173–182, 1970.
95. Schmidt, D. Diagnostik myasthenischer Augensymptome. *Klin. Mbonatsl. Augenheilkd., 167:* 651–664, 1975.
96. Baloh, R. W., and Keesey, J. C. Saccade fatigue and response to edrophonium for the diagnosis of myasthenia gravis. *Ann. N. Y. Acad. Sci., 274:* 631–641, 1976.
97. Metz, H. S., Scott, A. B., and O'Meara, D. M. Saccadic eye movements in myasthenia gravis. *Arch. Ophthalmol., 88:* 9–11, 1972.
98. Spector, R. H., Daroff, R. B., and Birkett, J. E. Edrophonium (Tensilon) infrared optokinetic nystagmography in the diagnosis of myasthenia gravis. *Neurology, 25:* 317–321, 1975.
99. Glaser, J. S. Myasthenic pseudo-internuclear ophthalmoplegia. *Arch. Ophthalmol., 75:* 363–366, 1966.
100. Metz, H. S. Myasthenia gravis presenting as internuclear ophthalmoplegia. *J. Pediat. Ophthalmol., 14:* 23, 1977.
101. Cogan, D. C., Yee, R. D., and Gittinger, J. Rapid eye movements in myasthenia gravis. I. Clinical observations. *Arch. Ophthalmol., 94:* 1083–1085, 1976.
101. Yee, R. D., Cogan, D. G., Zee, D. S., Baloh, R. W.,

and Honrubia, V. Rapid eye movements in myasthenia gravis. II. Electro-oculographic analysis. *Arch Ophthalmol., 94:* 1465–1472, 1976.

102. Selhorst, J. B., Stark, L., Ochs, A. L., and Hoyt, W. F. Disorders in cerebellar ocular motor control. I. Saccadic overshoot dysmetria. An oculographic, control system and clinic-anatomical analysis. *Brain, 99:* 497–508, 1976.

103. Dell'Osso, L. F., Abel, L. A., and Daroff, R. B. "Inverse latent" macro square wave jerks and macro saccadic oscillations. *Ann. Neurol., 2:* 57–60, 1977.

104. Shults, W. T., Stark, L., Hoyt, W. F., and Ochs, A. L. Normal saccadic structure of voluntary nystagmus. *Arch. Ophthalmol., 95:* 1399–1404, 1977.

Topics in Neuro-Ophthalmology

Edited by

H. Stanley Thompson, M.D.
Robert Daroff, M.D.
Lars Frisén, M.D.
Joel S. Glaser, M.D.
Michael D. Sanders, F.R.C.S.

WILLIAMS & WILKINS
Baltimore/London

Copyright ©, 1979
The Williams & Wilkins Company
428 E. Preston Street
Baltimore, Md 21202, U.S.A.

All rights reserved. This book is protected by copyright. No part of this book may be reproduced in any form or by any means, including photocopying, or utilized by any information storage and retrieval system without written permission from the copyright owner.

Made in the United States of America

Library of Congress Cataloging in Publication Data

Main entry under title:

Topics in neuro-ophthalmology.

Topics originally presented at a workshop in neuro-ophthalmology in the International symposia series sponsored by the Dept. of Ophthalmology of the University of Iowa and held in Iowa City, Nov. 10–12, 1977.
Includes index.
1. Neuro-ophthalmology—Congresses. I. Thompson, Herbert Stanley, 1932– [DNLM: 1. Ophthalmology—Congresses. 2. Eye-Innervation—Congresses. WW100 T674 1977]
RE725.T66 617.7 78-25658
ISBN 0-683-08178-0

Composed and printed at the
Waverly Press, Inc.
Mt. Royal and Guilford Aves.
Baltimore, Md 21202, U.S.A.