

# The Physiology and Neurology of Vergence Eye Movements: An Update.

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## Introduction

Human eye movements have been classified into three groups: reflex, voluntary and fusional (Bielschowsky, 1956). The reflex and voluntary eye movements are described as conjugate or versional movement which have the characteristics of both eyes moving in the same direction of gaze. Reflex eye movements are controlled by the vestibulo-ocular and optokinetic systems. These two systems have very short latencies and exist to stabilise the eyes for compensatory head movements. Voluntary eye movements are controlled by the saccadic and smooth pursuit systems. The saccadic system has high level velocity eye movements to re-fixate targets from different gaze positions, whereas the smooth pursuit system involves low level eye movements which provide the advantage of tracking slowly moving targets.

The vergence system is the controller for fusional eye movements. Unlike reflex and voluntary eye movements, innervation from the vergence centre will initiate disjugate movements of the eyes, that is, both eyes moving in opposite directions. This type of movement is important in maintaining the state of binocular fixation at various viewing distances. This paper aims to give a summary of the physiology of vergence eye movements and to highlight recent findings concerning the neurology of the vergence system.

## Types of Vergence Eye Movements

It has been well known that horizontal fusion has strongest motor control compared to vertical and torsional fusion. This motor fusional component is served by the vergence eye movement system. It has been well documented that horizontal vergence, especially convergence, is composed of several components. In 1893, Maddox (cited in Morgan 1983, p.16) first postulated the four main vergence components including: tonic, fusional, accommodation and proximal vergence. Later, in addition to these four components, Maddox described the additions of disparity, relative and voluntary convergence (Morgan 1980).

### Tonic

Due to the structure of the orbit, the anatomical position of the globe is somewhat divergent. The anatomical resting position is demonstrable during deep sleep or anaesthesia as opposed to the physiological resting position of the eyes which is noted in the absence of visual stimuli ie. in the dark. The anatomical divergent angle has been reported to vary from slight divergence (Cogan, 1956) to as much as 68 degrees of divergence (Mann cited in Owens and Leibowitz, 1983), and it is influenced by drowsiness, alcohol, anaesthetic agents, age and stress (Owens and Leibowitz, 1983).

During the state of waking consciousness, there is a continuous tonic innervation to the extraocular muscles to align the eyes in the parallel position, either with or without the presence of a stimulus (Schor, 1980; Morgan, 1980). Maddox (cited in Owens and Leibowitz, 1983) recognised that the magnitude of tonic convergence varied between individuals and that errors in tonic innervation could induce misalignment of the eyes known as heterophoria. Excess tonic vergence resulted in latent overconvergence (esophoria) while latent underconvergence (exophoria)

appeared to be the consequence of a deficiency in tonic vergence.

### *Disparity versus fusional vergence*

The motor response to an abrupt change in retinal disparity can be separated into two stages: the initiation and the completion (Jones and Stephens, 1989; Jones, 1983; Schor, 1980). The initial response is referred to as disparity vergence which is a coarse, fast, transient and open-loop mechanism. Disparity vergence is thought to be the primary motor response to disparate targets which can be large or quite dissimilar in characteristics (Stark, Kenyon, Krishnan & Ciuffreda, 1980; Semmlow, Hung, Horng & Ciuffreda, 1994). The completion or fusional vergence is a fine, slow, sustained and feature sensitive mechanism. Its movements bring residual disparity of the eyes to their final accurate bifoveal fixation position under a visual feedback control system (Stark, Kenyon, Krishnan & Ciuffreda, 1980; Semmlow, Hung, Horng & Ciuffreda, 1994). Fusional vergence only responds well to small disparities with the requirements that the images seen by each eye have many features in common (Semmlow, Hung, Horng & Ciuffreda, 1993). These components of the vergence movement system are made almost automatically, but they are not considered reflexes because visual stimuli must be conveyed to the visual cortex in order to induce ocular movements (Bielschowsky, 1956). These types of eye movements are elicited by disparate images and are therefore also considered as psycho-optical reflexes because they occur only when there is sensorial stimulation, that is, disparity of the retinal areas (Bielschowsky, 1956).

### *Accommodative*

The existence of accommodative vergence has been strongly postulated following Muller's experiment (Leigh & Zee, 1991). By asking a subject to fixate a moving target from distance to near with one eye while the other eye was covered, it was reported that the eye under the cover slowly converged as the target moved closer. This meant that the blurred stimulus not only stimulated the accommodation mechanism but also initiated the vergence system, and therefore there must be a link between accommodation and convergence. Accommodative vergence is described as being significantly reduced with age due to the presence of clinical presbyopia (Ciuffreda, Ong & Rosefield, 1993). It has been noted that accommodative vergence is reduced with increasing age as the accommodation becomes

weaker (Nuzzi et al. cited in Hokoda 1991). These authors stated that there is also an increase in proximal vergence with age to compensate for the reduction of accommodative vergence.

### *Proximal*

Proximal convergence is the ability to converge the eyes as a result of knowledge or awareness of the nearness of an object. Thus this component is variable in magnitude and involves more of a psychological basis (Hokoda & Ciuffreda, 1983). Proximal vergence accounts for 50% of the near vergence response under open looped conditions. The amount of proximal vergence is estimated by calculating the difference in the AC/A ratios calculated by heterophoria and the gradient methods. This value is thought to range from 0.5-2.0  $\Delta/D$  (convergence- $\Delta$ / distance-D) (Hokoda & Ciuffreda, 1983). Studies by Schapero and Nadell (1957) on the changes of accommodation and vergence in 16 subjects aged between 30 and 74 years (30-39 = 8 subjects; 40-49 = 6 subjects; >70 = 2 subjects) showed that proximal vergence reduced with age. However, Sheedy and Saladin (1975) claimed that proximal vergence remained constant in their study of twenty three subjects (13 non-presbyopic subjects aged 22-29, and 10 presbyopes aged 51-75). Recently, Hokoda and his co-workers (1991) studied the proximal vergence of 106 subjects aged between 6-47 years (mean age = 28.5). They showed that there was no significant correlation between proximal vergence and increasing age (Spearman's  $r = -0.06$ ). However, the number of subjects in each group was not equal. Most of the subjects were in the 21-30 and 31-40 groups, and there were only 12 subjects over 40 years of age. This therefore reflected the smallness of the presbyopic group which was not able to show a significant correlation between proximal vergence and increasing age.

### *Relative*

Relative convergence is the amount of convergence that can be changed in relation to a set amount of accommodation without producing diplopia (von Noorden, 1990). Conversely, relative accommodation is the amount of accommodation that can be changed in relation to a set amount of convergence without the perception of blur. von Noorden (1990) stated that these amounts could be modified with training. Exercise to produce convergence in excess of accommodation is referred to as positive relative vergence, whereas exercise to train accommodation in excess of convergence is known as positive relative

accommodation or negative relative vergence (von Noorden, 1990).

### **Voluntary**

The ability to perform convergence of the visual axes with effort under the absence of visual stimulus is known as voluntary vergence (Morgan, 1980; Eskridge, 1971). Voluntary vergences have similar characteristics to other voluntary eye movements such as saccadic or smooth pursuit movements. This means that the movements are controllable and can be varied in magnitude (Eskridge, 1971). However, not everybody can converge their eyes voluntarily, and this ability appears to require training or practice (Bielschowsky, 1956; Eskridge, 1971; Morgan, 1980).

## **Physiology of vergence eye movements**

### **Stimulus for vergence eye movements**

The vergence system is comprised of several components and there are therefore several stimuli that can initiate vergence; a blurred stimulus will initiate accommodative vergence, a knowledge of nearness will initiate proximal vergence and the disparity vergence will be induced by retinal disparity. However, the two primary stimuli that evoke the initiation of convergence are the disparity and blur of the stimulus, which ultimately initiates fusional and accommodative vergence (Leigh & Zee, 1991; Zuber, 1971). Accommodative and disparity vergence have generally been considered as the two main components for the alignment of the eyes during convergence, whereas proximal convergence has traditionally been considered as secondary. Wick (1985) claimed that proximal vergence comprised up to 70% of the steady state near vergence response. Joubert and Bedell (1990) found that the contribution of proximal vergence varied from 35-64% of the total vergence responses. The most recent study by North and associates (1993) comprised of 18 subjects, aged 18-23, with normal binocular vision, looked at the contribution of the proximal, accommodative and disparity vergences in the normal vergence responses. Their results showed that proximal vergence was the most important component, contributing 45% to the total vergence response, followed by disparity (41%) and accommodative vergence (14%). Wick and Bedell (1989) studied seven normal binocular vision adult college students and showed that proximal vergence had a greater velocity than disparity and accommodative vergence, and therefore it was the major

component for rapid eye alignment. These findings were confirmed by Wick and Bedell (1992). Overall, the initiation of a particular component of vergence depends upon the nature of the stimulus. In the condition where fixation changes rapidly from distance to near, then proximal vergence is probably the main component to initiate this change. If the fixation stimulus moves slowly towards the viewer, the accommodative and disparity vergences are thought to be the main components for the vergence response. It is important to note that the total vergence movement is an additive process, therefore all the components are important for maintaining binocular vision. However, one component might be more important than the others under differing conditions.

### **Dynamic properties of vergence eye movements**

Vergence eye movements have relatively long latencies. The average latency for vergence movements is approximately 160 msec, which is the second longest latency after the saccadic system which has a latency of 200 msec (Gay, Newman, Keltner & Straud, 1974). There are also some variations in latency of different types of vergences, such as fusional vergence (160 msec) which has a shorter latency than accommodative vergence (200 msec) (Leigh & Zee, 1991). The vergence system also has the slowest eye movement velocity of approximately 20°/sec (Gay et al., 1974). The dynamic properties of vergence eye movements are that they are very slow and it might take as long as one second to complete. It is thought that the velocity of vergences is increased when the target of interest changes its position across the visual field as well as in depth (Leigh & Zee, 1991). This means that the vergence movement is faster if it is combined with a versional movement. Furthermore, it has been suggested that the command signal for pure vergence movements is a step (tonic) change in innervation to the extraocular muscles. Unlike the saccades, the dynamic properties of vergence responses are considerably more variable. They are related to the type of the stimulus, that is, disparity, blur, size, the condition of viewing and whether or not it is associated with a saccade or a blink (Leigh & Zee, 1991).

Compared to horizontal vergence, vertical vergence is much slower, taking as long as 8 seconds for completion (Kertesz, 1983). Vertical fusion cannot usually overcome disparities of more than a degree, even though part of the fusional response ( $\approx 20\%$ ) is accomplished by sensory not motor processes (Kertesz, 1983). Cyclodisparities also elicit cyclotorsional movements but like the

vertical vergence, they are slow and have a limited range, and the motor component is very weak because there is a strong sensory component to cyclofusion (Kertesz & Jones 1970, and Kertesz, 1983).

### *Accuracy of vergence eye movements*

There is a constant state of error in vergence eye movements. Vergence movements recorded by direct photographs, corneal reflections and oculography show steady state errors varying from 2 minutes of arc to as large as  $2^\circ$  (Zuber, 1971). Recently, Cornell (1995) claimed that these errors could be as high as  $8.2^\circ$  for peripheral and  $5.5^\circ$  for central targets in normal subjects. These measurements were recorded by the Ober2 infrared eye movement system. It seems that the level of accuracy in vergence eye movements is inversely proportional to Panum's fusional area. When Panum's fusional area is narrow, the vergence movements need to be more precise to keep the targets within Panum's fusional area so that binocular single vision is appreciated. Since Panum's fusional area varies with central and peripheral fixation, and with stimulus parameters, the level of accuracy in vergence eye movements will depend upon the nature of the stimuli and the test conditions.

### *AC/A and CA/C ratios*

The relationship between accommodation (A) and accommodative linked convergence (AC) can be expressed as the AC/A ratio (prism diopters/sphere diopters). As the vergence angle ( $V_0$ ) in prism diopters is equal to the IPD (cm) divided by the viewing distance 'd' (m), the calculated ratio would be 6:1, given that the average interpupillary distance is six centimetres. However, the clinical AC/A ratio is usually smaller (4:1). Thus, during binocular viewing of near objects, disparity/fusional vergences must also be functioning to align the axis correctly. It has been noted that the AC/A ratio remains relatively constant with age (Hokoda, Rosefield and Ciuffreda, 1991). Contrary, findings by Bruce, Atchison & Bhoola (1995) show that the AC/A ratio increased (average 0.126  $\Delta/D$  per year) with age. Yet, not only is convergence (C) linked to accommodation, but accommodation is also linked to vergence (convergence linked accommodation) (CA/C). The clinical CA/C ratio, the amount of accommodation in sphere diopters induced per prism dioptre of convergence, is typically about 0.1:1. In fact, this ratio should be about 0.16:1 if the amount of convergence linked accommodation were just equal to that required for clear vision at all distances. The CA/C ratio is thought to decrease

with age (Bruce et al., 1995). Bruce and his co-workers (1995) indicated that the mean CA/C ratio decreased from 0.1D/ $\Delta$  at the age of 20 to 0.03D/ $\Delta$  at the age of 40. Overall, because of the differences in the exactness of AC/A and CA/C ratios, accommodative and fusional drives must work together to enable the acquisition of clear, single objects at all distances.

## **Neurology of vergence eye movements**

### *Control centre for vergence eye movements*

It has been well described that the paramedian pontine reticular formation (PPRF) is the horizontal gaze control centre for versional eye movements and its major output is to the ipsilateral abducens nucleus. The abducens nuclei have two types of neurons: abducens motoneurons which supply the ipsilateral lateral rectus and abducens internuclear neurons whose axons decussate at the nucleus level and ascend together with the medial longitudinal fasciculus (MLF). These axons synapse with the medial rectus motoneurons of the oculomotor nucleus. The axons from the medial rectus motoneurons supply the ipsilateral medial rectus muscle. Lesions at the MLF give a clinical syndrome known as internuclear ophthalmoplegia (INO) which has a characteristic limitation in adduction of the ipsilateral eye when attempting a versional movement (conjugate eye movements to the opposite side of the lesion). It is interesting that the vergence eye movements are usually unaffected even in the case of bilateral INO. Based on these phenomena many authors (Leigh & Zee, 1991; Lawler & Cowey, 1986; Cogan, 1956; Mays, 1984) have agreed that the vergence system is neurologically independent of the conjugate eye movement system.

The possible localisation of a vergence control centre has been reported by many authors. A study of the oculomotor nucleus morphology by Buttner-Ennever and Akert (1981) showed that the medial rectus motoneurons has three distinct segregations of cells named A, B & C. Group A cells are located in the ventral and rostral parts of the oculomotor nucleus (OMN). The average diameter of cells in group A is  $26\mu\text{m}$  (Buttner-Ennever & Akert, 1981). B group cells are situated dorsally and caudally, and they have an average diameter of  $30\mu\text{m}$  (Buttner-Ennever & Akert, 1981). Group C cells are located dorsomedially and rostrally. This cell group has its diameter (average diameter =  $18\mu\text{m}$ ) significantly smaller than group A and B cells,

and it supplies smaller muscle fibres of the medial recti (Buttner-Ennever & Akert, 1981).

Therefore, the group C cells are thought more likely to be involved in generating slow eye movements such as vergence, but there is no physiological evidence to support this hypothesis (Buttner-Ennever & Akert, 1981).

Early studies showed that cells in the mesencephalic reticular formation change their activities during vergence eye movements. Schiller (cited in Mays, 1984) showed a small number of neurons recorded in the dorsal lateral region of the caudal part of the oculomotor nucleus complex, whose activities increased during vergences. Later, Mays (1984) made a thorough study of such neurons, and showed that there were cells located dorsal and dorsal lateral, approximately 2mm within the medial rectus motoneurons of the oculomotor nucleus (OMN), that changed their firing rate approximately linearly to the vergence angle. Recently, Judge and Cumming (1986) showed that most of the near response cells were recorded in a region extending only 1mm above the OMN and 2.5mm above the magnocellular red nucleus (mRN). The majority of these cells were close to the dorsal limit of the oculomotor or red nuclei, and a few cells may have been in the pretectum or rostral superior colliculus. According to the changing activities of these cells, Mays (1984) subdivided these cells into two main groups: convergence and divergence cells.

### **Convergence cells**

Mays (1984) stated that there were neurons (68 cells) near the oculomotor nucleus that increased their firing rate with convergence eye movements, but that there was no change in the activity of these cells for purely conjugate eye movements. During steady fixation at any vergence angle, the firing rate of these cells is constant. Furthermore, the firing rate of convergence cells is a linear function of the vergence angle and is unaffected by the direction of conjugate gaze. The average firing pattern over the vergence angle is  $10.4 \text{ spikes.s}^{-1}.\text{deg}^{-1}$ . Once the near fixation has stabilised, firing rate of these cells remains nearly constant.

### **Divergence cells**

The divergence cells were found intermixed with the convergence cells (Mays, 1984). These cells have a steady firing rate inversely proportional to the vergence angle, that is, the rate decreases during convergence and increases during divergence. There is no change in the firing rate during conjugate eye movements. These cells have an average firing rate of  $10.3 \text{ spikes.s}^{-1}.\text{deg}^{-1}$

(Mays, 1984).

Mays and Porrer (1984) also reported that there was a group of cells found in the vicinity of these vergence cells that also changed their activities to vergence movements. The activities of these cells were thought to be related to vergence velocity. Later, this finding was confirmed by Mays, Porter, Gamlin and Tello (1986). According to the activities of these cells in response to vergence movements, they have been classified into three main types; convergence burst cells, burst tonic cells and divergence burst cells (Mays et al., 1986).

### **Convergence burst cells**

These cells give a vigorous burst of activity just before and during all convergence eye movements, but are not modulated during purely conjugate eye movements or during fixation. There are about 58 cells that have this characteristic and they have an average firing rate of  $4.45 \text{ spikes.s}^{-1}.\text{deg.s}^{-1}$  (Mays et al., 1986). The average amplitude, as spikes increase, is about  $6.37 \text{ spikes/deg}$  (Mays et al., 1986). Most convergence burst neurons are found ventral to the mesencephalic reticular formation, dorsal and lateral to the oculomotor nucleus. Some convergence burst cells are also found in a more dorsal region which may also include some pretectal nuclei, rostral to the superior colliculus (Mays et al., 1986)

### **Burst tonic cells**

Most of these cells burst for a small vergence movement (up to  $2^\circ$ ) and show little tonic activity unless a large vergence is made (Mays et al., 1986). These tonic rates are indicated to be proportional to the vergence angle (Mays et al., 1986). Most burst tonic cells are located at the area similar to the near response cells, and some are located approximately 5mm dorsal and 5mm lateral to the oculomotor nucleus (Zee & Levi, 1989).

### **Divergence burst cells**

This cell type has a far smaller number (8 cells). Similar to the convergence burst cells, these cells only increase their firing rate just before and during divergence (Mays et al., 1986). The divergence burst cells are often found in the ventral region of the vergence angle cells, and their firing rates are correlated to divergence velocity (Mays et al., 1986).

### **The activities of medial rectus motoneurons during vergence eye movements**

Robinson and Keller (1972) reported that the medial rectus motoneurons displayed a step

change in firing rates in response to vergence movements. This means that at the beginning of each movement, the rates change abruptly to a new level and stay there both during and after the movements. Later studies by Mays and Porter (1984) showed that there was a gradual change during symmetrical vergence. Mays et al. (1986) stated that near response cells (NRCs) could only carry either eye position or velocity signals to the medial rectus motoneurons. Recently, Zhang, Gamlin and Mays (1991) reported that these cells carried both eye position and vergence velocity. This has been confirmed by Gamlin and Mays (1992) by using single unit recording techniques. In addition, Zhang, Gamlin & Mays (1991) reported that NRCs are predominantly related to vergence and not accommodation, as reported by Judge & Cumming (1986). However, Zhang, Mays and Gamlin (1992) suggested that most of NRCs were driven by both the blur and disparity controller but differ in their accommodative and vergence coefficients. None of these cells however, had a high coefficient for both accommodation or vergence.

#### *Internuclear pathways of vergence system*

Oculomotor neurons (III CN) change their activities during versional as well as vergence eye movements suggesting that both vergence and versional eye movement commands are joined at this level before the signals are sent to the extraocular muscles. However, it is obvious that the connecting pathways between the vergence control centre and the OMN will certainly not travel through the MLF. Cogan (1956) suggested that the supranuclear pathways for vergence were along the anterior branchia and the superior colliculi rather than by way of the pons. Mays (1984) claimed that abducens internuclear axons carried only versional control signals. However, Gamlin and associates (1989) reported some inappropriate signals sent to the MLF during convergence.

Mays (1984) and Judge & Cumming (1986) suggested that convergence and divergence cells provided a monosynaptic drive to the medial rectus motoneurons. By using an antidromic microstimulation technique, Nakao's (1986) experiment in twenty-four anaesthetised adult cats showed that the neurons in the vicinity of the oculomotor nucleus projected directly to the medial rectus subdivision of oculomotor nucleus. Nevertheless, since the animals were paralysed, there was no evidence to support that these cells being near response cells. Recently, by using a similar technique to the one described in Nakao's experiment, Zhang, Gamlin and Mays (1991) conducted a study on two trained monkeys to

identify the cells that project to the medial rectus neurons of the oculomotor nucleus and to see whether these cells were related to the NRCs. Their results showed that there were twenty-eight cells that were antidromatically activated from the ipsilateral medial rectus neurons and that these cells also behaved as NRCs. This was the first electrophysiological evidence to support the direct monosynaptic projection from NRCs to medial rectus motor neurons (MMNs) of the oculomotor nucleus.

There is still a lack of evidence showing whether the projection of the NRCs to the MMNs is ipsilateral, contralateral or bilateral. Zhang et al. (1991) claimed that failure of the NRC to activate from the contralateral oculomotor nucleus suggested that vergence input to the medial rectus neurons was ipsilateral. However, it is already known that symmetrical vergence needs input to be sent to the MMNs from both sides of the brain. Furthermore, unilateral electrical stimulation of the midbrain where NRCs are located causes adduction of both eyes. If direct input to the medial rectus motoneurons occurs ipsilaterally, then it is possible that the NRCs on both sides of the brain have a common input or are cross-coupled (Zhang et al., 1991).

Many authors have provided evidence that the abducens nucleus decreases its firing rate during convergence and increases its firing rate during divergence (Robinson & Keller 1972, Mays 1984, Judge & Cumming, 1986). If the vergence commands pass directly to the oculomotor nucleus, then how are the abducens motoneurons receiving the vergence signal during disjugate eye movements? Leigh and Zee (1991) suggested the possibility of a projection from the interneurons (dorsal to the oculomotor complex) and projection to the ipsilateral and contralateral abducens nuclei. By using a double retrograde labelling technique in 12 adult cats, Maciewicz and Phipps (1983) provided evidence that a small percentage (16%) of the internuclear oculomotor neurons had bilateral projection to the abducens nucleus. Mays and Porter, (1984) reported that only 2/28 abducens motor neurons had the characteristic related to vergence, that means there was a significant increase in firing rate during vergence movements while decreasing the activity for conjugate eye movements.

Clendaniel and Mays (1994) studying 4 monkeys, identified 18 oculomotor internuclear neurons (OINs). These cells behaved similarly to medial rectus motoneurons during vergence and versional eye movements and non OINs sensitive to vertical eye position. Microstimulation of the

oculomotor nucleus where both the OINs medial rectus motoneurons were located, resulted a large adducting of the ipsilateral eye and a small abducting of the contralateral eye (could near response cells be versional eye movement response cells?). This evidence suggested that most of these cells innervated the contralateral abducens nucleus. Lidocaine injection to the OINs location resulted in hypometric and slowed adducting saccades to the contralateral side of the injection site that suggested crossed OIN pathways are excitatory. However, these signs have not been reported in a complete third nerve palsy clinically. Are OINs only for versions but not vergences?

### **Supranuclear control of vergence eye movements**

Mays (1984) claimed that there was some vergence paralysis due to lesions at the midbrain following trauma but the vergence centre could not be localised because this usually involved multiple lesions. Some of the cortical centres which are thought to have a role in vergence movements include: superior colliculus, cerebellum, frontal eye fields, occipital lobe, parietal lobe.

Leigh and Zee (1991) reported that stimulation of the pontine tegmentum between the two MLF, or in the third nerve nucleus itself, produces vergence movements. Further more, ablations of the cerebellum in monkeys transiently impairs vergences. Electrical stimulation of Brodman's areas 19 and 22 in the occipital cortex gives different combinations of the components of the near triad, and stimulation of the frontal eye fields produces convergence movements (Leigh and Zee, 1991). Bilateral stimulation of the frontal and occipital lobes has been done (Cogan, 1956), but the observations have been too few and too inexact to permit localisation. Weakness of convergence has followed bilateral occipital lobe injuries, ablation of the cortex around the angular gyri has been reported to result in paralysis of convergence with a disturbance of depth perception (Cogan, 1956).

Westheimer and Blair (1973) examined vergence eye movements on four monkeys who had had cerebellectomies. The results showed that no vergence was demonstrated after a complete removal of the cerebellum and suggested that the cerebellum played an important role for vergence as well as versional eye movements.

Lawler and Cowey (1986) studied the effect of bilateral pretectal and superior colliculus lesions on binocular vision. Nine monkeys with different sites of bilateral cortical ablations were included; three monkeys who had areas 5 and 7 of the parietal lobes ablated, three other monkeys who had

inferotemporal ablations and another three had frontal eye fields (area 8) ablated. The three monkeys who had frontal eye fields ablated, then had bilateral superior colliculi ablated three months later. These results showed that those monkeys with superior colliculus and frontal eye field ablation demonstrated more missearching errors when they performed under binocular viewing conditions. The authors indicated that searching errors were due to diplopia and were only evident at near, which was thought to be caused by a deficiency in vergences. Since the monkeys had both superior colliculi and frontal eye field ablations, and also there was no visual discrimination task given to the monkeys before the superior colliculi ablation, it could not be stated that limitations in vergences were due to lesions of superior colliculi. There were minimal missearching errors due to parietal lesions and no significant errors resulted from inferotemporal lesions.

Otsuka, Maekawa, Takeda, Uede and Chiba (1988) reported the case of a thirty-one year old man who had blurred vision and diplopia due to accommodative and vergence paralysis following a middle cerebral artery occlusion. Recently (1993), Ostuka reviewed horizontal eye movements of a nineteen year old man with arteriovenous malformation with haemorrhage in the right cerebellum (which was revealed on arteriography and computer tomography). Magnetic resonance imaging showed a haematoma located on the right, medial and inferior cerebellar peduncles and the hemispheres. Apart from gaze evoked nystagmus, cogwheeling smooth pursuit, hypermetric right saccades and sometimes hypometric left saccades, the vergence eye movements were absent. Accommodation was normal and pupils were constricted at near. The peak velocity of horizontal saccades was within the normal range that indicated the burst neurons in the PPRF and motoneurons were still intact.

Studies of the frequency of convergence insufficiency in traumatic brain injury (TBI) on 98 patients in the Loewenstein Rehabilitation Hospital (72 follow-up and 26 hospitalised patients) by Cohen, Groswasser, Barchadski and Appel (1989), showed that 42% of follow-up patients and 38% of hospitalised patients had insufficiency of convergence. The authors also noted that convergence insufficiency was significantly associated with dysphasia and cognitive disturbance but was not associated with behavioural disturbances. The authors claimed that long standing vergence insufficiency is fairly common following severe TBI.

## Conclusion

In conclusion, the existence of the vergence eye movement system facilitates binocular fixation at various distances. The cortical areas that have a role in vergence movements are thought to be the frontal eye fields, Brodman's areas 19 and 22 in the occipital cortex, the superior colliculus, parietal lobe and the cerebellum. The supranuclear pathways that connect these cortical areas to the vergence centre are still unclear, however, it is thought to be via the anterior branchia and the superior colliculi rather than by way of the pons. The vergence centre is located dorsal and dorsolateral to the oculomotor nucleus. Outputs from the vergence centre project ipsilaterally to the medial rectus motoneurons. This projection is thought to be monosynaptic and it is cross-coupled. Unfortunately, there is little understanding about the neurology of vertical and torsional vergence. These types of vergences are very small in amplitude and usually do not exist in normal free-space viewing conditions. Overall, the neurophysiological aspects of horizontal vergence eye movements have been studied more thoroughly over the last decade. However, most of these works have been concentrated on the midbrain area. There are still many doubts about the higher vergence control areas and their projections to the vergence centre. Therefore, more studies related to the supranuclear pathways need to be done in the future to give a better understanding of the neurology of the vergence eye movement system.

## References

- Bielschowsky A. Lecture on Motor Anomalies. 1956, Dartmouth Publications.
- Bruce AS, Atchison DA, Bhoola H. Accommodative-Convergence Relationships and Age. *Invest Ophthalmol Vis Sci.* 1995; 36(2): 406-13.
- Buttner-Ennever JA, Akert K. Medial rectus Subgroups of the Oculomotor Nucleus and Their Abducens Internuclear Input in the Monkey. *J Comparative Neurol.* 1981; 197: 17-27.
- Ciuffreda, KJ, Ong, E & Rosenfield, M. Tonic Vergence, Age and Clinical Presbyopia. *Ophthalmol.* 1993; 13: 313-315.
- Clendaniel RA, Mays LE. Characteristics of Antidromically Identified Oculomotor Internuclear Neurons During Vergence and Versional Eye Movements. *J Neurophysiol.* 1994; 71 (3): 1111-27.
- Cogan GD. Neurology of the Ocular Muscles. 2nd Edition. Charles Thomas, 1956.
- Cohen M, Groswasser Z, Barchadeski R, Appel A. Convergence Insufficiency in Brain-Injured Patients. *Brain Injury.* 1989; 3(2): 187-91.
- Cornell E. Binocular Responses to Monocular Placement of a 10Δ Base Out Prism: Part I. Initial Versions and Vergences; A Pilot Study in 30 Normals. *Binoc Vis Eye Mus Surg Qtrly.* 1995; 10(1) : 39-46.
- Eskridge, JB. An Investigation of Voluntary Vergence. *Am Jnl Optom and Arch Am Acad Optom.* 1971; 48, (9): 741-746.
- Gamlin PD, Mays LE. Dynamic Properties of Medial Rectus Motoneurons During Vergence Eye Movements. *Journal of Neurophysiol.* 1992; 67(1): 64-74.
- Gamlin PD, Gnadt JW, Mays LE. Abducens Internuclear Neurons Carry an Inappropriate Signal for Ocular Convergence. *J Neurophysiol.* 1989; 62(1): 70-81.
- Gamlin PD, Gnadt JW, Mays LE. Lidocaine-Induced Unilateral Internuclear Ophthalmoplegia: Effects on Vergence and Conjugate Eye Movements. *J Neurophysiol.* 1989; 62(1): 82-95.
- Hokoda SC & Ciuffreda KJ. Theoretical and Clinical Importance of Proximal Vergence and Accommodation. In CM. Schor & KJ. Ciuffreda (Eds.) *Vergence Eye Movements: Basic and Clinical Aspect.* 1983; pp. 75-97. Butterworths.
- Hokoda SC, Rosenfield M, Ciuffreda KJ. Proximal Vergence and Age. *Optom Vis Sci.* 1991; 68(3): 168-172.
- Jones R. Horizontal Disparity Vergence. In Schor CM & Ciuffreda KJ. *Vergence Eye Movements: Basic and Clinical Aspects.* Butterworths, 1983. 297-326.
- Jones R, Stephens GL. Horizontal Fusional Amplitude. *Invest Ophthalmol Vis Sci.* 1989; 30 (7): 1638-42.
- Joubert, C & Bedell, HE. Proximal Vergence and Perceived Distance. *Optom and Vis Sc.* 1990; 67: 29-35.
- Judge SJ, Cumming BG. Neurons in the Monkey Midbrain with Activity Related to Vergence Eye Movements and Accommodation. *J Neurophysiol.* 1986; 55(5): 915-30.
- Kertesz AE, Jones RW. Human Cyclofusional Response. *Vis. Res.* 1970; 10: 891-6.
- Kertesz AE, Vertical and Cyclofusional Disparity Vergence. In Schor CM & Ciuffreda KJ. *Vergence Eye Movements: Basic and Clinical Aspects.* Butterworths, 1983. 317-348.
- Lawler KA, Cowey A. The Effects of Pretectal and Superior Collicular Lesion on Binocular Vision. *Exp Brain Res.* 1986; 63(2): 402-8.



- Leigh RJ, Zee DS. The Neurology of Eye Movements. 2nd Edition. Philadelphia 1991. 264-290.
- Maciewicz R, Phippa BS. The Oculomotor Internuclear Pathway: A Double Retrograde Labeling Study. *Brain Res.* 1983; 262: 1-8.
- Mays LE, Porter JD. Neural Control of Vergence Eye Movements: Activity of Abducens and Oculomotor Neurons. *J Neurophysiol.* 1984; 52(4): 743-61.
- Mays LE. Neural Control of Vergence Eye Movements: Convergence and Divergence Neurons in Midbrain. *J Neurophysiol.* 1984; 51(5): 1091-108.
- Mays LE, Porter JD, Gamlin PD, Tello CA. Neural Control of Vergence Eye Movements: Neurons Encoding Vergence Velocity. *J Neurophysiol.* 1986; 56(4): 1007-21.
- Morgan MW. The Maddox Classification of Vergence Eye Movements. *Am J Optom Physiol Optics.* 1980; 57(9): 537-539.
- Morgan MW. The Maddox Analysis of Vergence. In Schor CM & Ciuffreda KJ. *Vergence Eye Movements: Basic and Clinical Aspects.* Butterworths, 1983. Pg. 15-21.
- Nakao S, Shiraishi Y, Miyara T. Direct Projection of Cat Midbrain Tegmentum Neurons to the Medial Rectus Subdivision of the Oculomotor Complex. *Neuroscience Letters.* 1986; 64(2): 123-8.
- North, RV, Henson, DB & Smith, TJ. Influence of Proximal, Accommodative and Disparity Stimuli Upon the Vergence System. *Ophthalm Physiol Optics.* 1993; 13: 239-243.
- Ohstuka K, Maekawa H, Takeda, Ude N, Chiba S. Accommodation and Convergence insufficiency with Left Middle Cerebral Artery Occlusion. *Am J Ophthalmol.* 1988; 106(1): 60-4.
- Ohstuka K, Maekawa H, Sawa M. Convergence Paralysis after Lesions of the Cerebellar Peduncles. *Ophthalmologica.* 1993; 206(3): 143-8.
- Owens, AD & Leibowitz, HW. Perceptual and Motor Consequences of Tonic Vergence. In Schor CM & Ciuffreda KJ. (Eds.) *Vergence Eye Movements: Basic and Clinical Aspect.* 1983 pp.25-74. Butterworths.
- Robinson DA, Keller EL. Aducens Unit behaviour in the Monkey During Vergence Movements. *Vis Res.* 1972; 12(3): 369-82.
- Schapiro M, Nadell M. Accommodation and Convergence Responses in Beginning and Absolute Presbyopes. *Am J Optom Arch Am Optom.* 1957; 34: 606-23.
- Schor CM. Fixation Disparity: A Steady State Error of Disparity-Induced Vergence. *Am J Optom Physiol Optics.* 1980; 57(9): 618-31.
- Semmlow JL, Hung GK, Horng JL, Ciuffreda KJ. Initial Control Component in Disparity Vergence Eye Movements. *Vis Res.* 1993; 33(5): 691-708.
- Semmlow JL, Hung GK, Horng JL & Ciuffreda KJ. (1994) Disparity Vergence Eye Movements Exhibit Preprogrammed Motor Control. *Vis Res.* 34(10): 1335-43.
- Sheedy JE, Saladin JJ. Exophoria at Near in Presbyopia. *Am J Optom Physiol Optics.* 1975; 52: 474-81.
- Stark L, Kenyon RV, Krishnan VV, Ciuffreda KJ. Disparity Vergence: A Proposed Name for a Dominant Component of Binocular Vergence Eye Movements. *Am J Optom Physiol Optics* 1980; 57(9): 606-9.
- von Noorden, GK. *Binocular Vision and Ocular Motility: Theory and Management of Strabismus.* 1990. (4th ed.). Mosby.
- Westheimer G, Blair MS. Oculomotor Defects in Cerebellectomised Monkeys. *Invest Ophthalmol Vis Sci.* 1973; 12(8): 618-21.
- Wick B, & Bedell HE. Rapid and Slow Velocity Vergence Eye Movements. *Ophthalmic Physiol Optics.* 1992; 12: 420-4.
- Wick B, & Bedell HE. Magnitude and Velocity of Proximal Vergence. *Inves Ophthal Vis Sci.* 1989; 30 (4): 755-760.
- Wick B. Clinical Factors of Proximal Vergence. *Am Jnl Optom & Physio Optics.* 1985; 62: 1-18.
- Zee DS, Levi L. Neurological Aspects of Vergence Eye Movements. *Rev Neurol (Paris).* 1989; 145 (8-9): 613-20.
- Zhang Y, Gamlin PD, Mays LE. Antidromic Identification of Midbrain Near Response Cells Projecting to the Oculomotor Nucleus. *Exp Brain Res.* 1991; 84(3): 525-8.
- Zhang Y, Mays LE, Gamlin PD. Characteristics of Near Response Cells Projecting to the Oculomotor Nucleus. *J Neurophysiol.* 1992; 67(4): 944-60.
- Zuber, BL. Control of Vergence Eye Movements. In P. Bach-Y-Rita, CC. Collins & EJ. Hyde (Eds.). *The Control of Eye Movements.* 1971: pp. 447-471. Academic Press.