Eur Arch Psychiatr Neurol Sci (1989) 239:3–8

European Archives of Psychiatry and Neurological Sciences

Supratentorial Structures Controlling Oculomotor Functions and Their Involvement in Cases of Stroke

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Summary. A study is presented mainly of the supratentorial structures that play an important role in saccadic eye movements and smooth pursuit. Eye-movement impairments associated with stroke in the corresponding brain region are then described.

Key words: Eye movements – Impairment after stroke

Introduction

There are five different kinds of eye movements: smooth pursuit, saccades, optokinetic nystagmus, vestibulo-ocular reflex and convergence. In the following, mainly saccadic and smooth-pursuit systems are discussed.

Figure 1 is a modification of a scheme devised by Wurtz and Hikosaka (1986) to illustrate the saccadic system in monkeys and probably also in man. The important role of the frontal eye field (FEF) or area 8 has been well established by both stimulation (Ferrier 1974; Robinson and Fuchs 1969) and single-unit studies (Mohler et al. 1973; Wurtz and Mohler 1976; Bruce and Goldberg 1985; Goldberg and Bruce 1986). Neurons in the FEF have anticipatory, visual and movement-discharge patterns in all purposeful saccadic eye movements. Neuronal activity with movement closely resembles activity in the intermediate layers of the superior colliculus (SC) with one major exception: in the SC, movement-related activity occurs before *all* saccades, whereas in the arcuate FEF it only occurs before *purposeful saccades*. Obviously, the FEF and SC work in concert most of the time, although direct projections from the FEF to the reticular formation (RF) of the brain stem allow the FEF to effect saccades independently of the colliculus. Thus, stimulation of the arcuate FEF in monkeys remains effective following SC lesions, whereas the ability of electrical stimulation of the striate and posterior parietal cortex to elicit saccades is lost (Keating and Gooley 1988). Similarly, removal of either the SC or FEF alone does not eliminate visually guided saccades, but removal of both structures together eliminates both visually guided and remembered saccades. Therefore, it is safe to state that saccadic eye movements are controlled by parallel channels.

A third pathway from the FEF extends via the caudate nucleus (c) to the substantia nigra (SN) and the SC. Anatomical physiological and pharmacological experiments suggest that the SN produces GABA-mediated tonic inhibition in SC cells. The signal of these SN cells is conveyed as a pause in this inhibition, which has been shown to occur before saccades to both visual and remembered targets.

In summary, the FEF and SC constitute an interface between the visual and the oculomotor system.

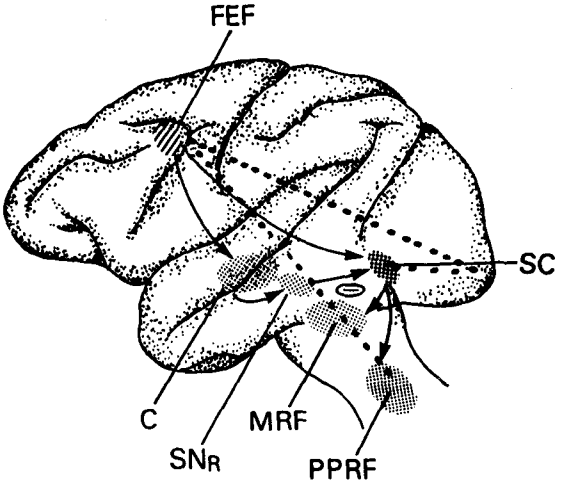

Fig. 1. The saccadic system in monkey (for details see text)

This article was presented in part at the Symposium on Eye Movements and Psychopathology, Berlin, 23–24 June 1988

Both the FEF and SC use spatial maps for target localization, i.e. the direction and amplitude of a saccade is determined by the spatial distribution of active neurons in a motor error map.

Oculomotor neurons, however, need a different code. There, the direction of movement is determined by the set of neurons activated for different muscles and the amplitude by the duration of burst-unit activity. According to Henn and Hepp (1986), a lateral movement of the abducens muscle in monkeys involves activation of the motor neuron during 30 ms for a 10° saccade and during 50 ms for a 30° saccade.

Translation of the spatial map arrangement into a temporal code is effected in the paramedian pontine reticular formation (PPRF) for horizontal eye movements and in the rostral interstitial nucleus of the median longitudinal fasciculus (riMLF) for vertical saccades (Bender 1980; Büttner-Ennever et al. 1982; Henn et al. 1984; Kömpf et al. 1979).

In considering smooth pursuit, one has to realize that there are different kinds of smooth eye movements (Eckmiller 1987) and that these might use different tracking procedures as well as different channels and interfaces to the oculomotor system (Tusa and Ungerleider 1988). Thus, there is much evidence, for example, that foveal smooth pursuit is, at least in part, processed differently from the slow phase of optokinetic mystagmus (OKN).

Recently, Eckmiller (1987) presented a rather complicated scheme of the smooth-pursuit system, which cannot be reviewed here in detail. The most important structures activated in smooth-pursuit eye movements are the retina, the dorsal lateral geniculate nucleus (LGN) and visual area 1 (V1 or area 17). V1 has been shown to contain direction-selective neurons as well as neurons with special sensitivity to slow retinal image velocity (Poggio and Talbot 1982). These data suggest that V1 makes important contributions towards the control of smooth-pursuit eye movements, i.e. target-background discrimination, monitoring of target position, target velocity, and target movement direction relative to the foveal centre.

The next structure (Fig. 2) involved in smooth pursuit is the middle temporal visual area (MT), which in monkeys is located in the posterior bank of the superior temporal sulcus. It has been shown to receive projections from area V1. MT encodes direction, speed and binocular disparity of visual targets moving within the contralateral field (Maunsell and Van Essen 1983a, b). The MT is well suited to the analysis of visual motion in three-dimensional space. It also seems to encode the unitary motion of moving patterns (Movshon et al. 1985).

Small ibotenic-acid lesions in the MT produce bidirectional tracking deficits restricted to the corresponding retinotopic portion of the contralateral visual field. The tracking deficits result in a bidirectional disturbance of smooth-pursuit eye movements in the contralateral field and also lead to inaccurate saccades to moving targets (Newsome et al. 1985). Saccades to stationary targets remain unimpaired.

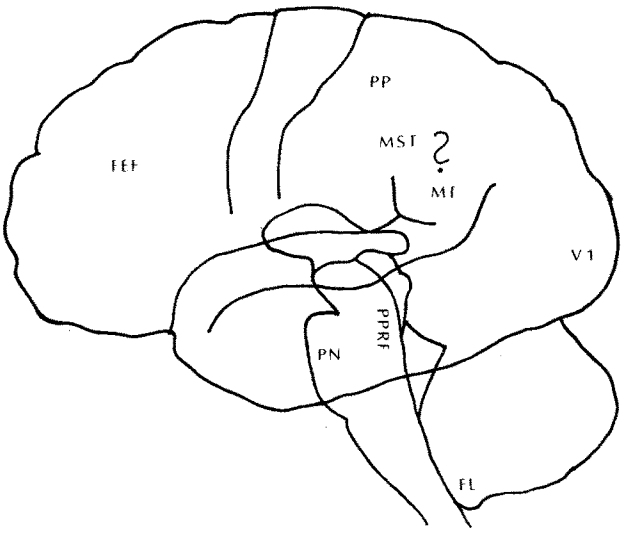

Fig. 2. Cerebral structures involved in smooth pursuit (for details see text)

Another important structure involved in smooth pursuit has recently been identified in monkeys (Wurtz and Newsome 1985) as containing neurons that encode both visual-motion information and eye-movement signals. This is the medial superior temporal area (MST) just adjacent to the MT. In monkeys, lesions of the MST, like those of the MT, produced a bidirectional retinotopic deficit in the contralateral hemifield (Dürsteler et al. 1986, 1987). But a unidirectional asymmetry of smooth pursuit in both hemifields was observed as well. The unilateral asymmetry of smooth pursuit in both hemifields is obviously not a disturbance of visual processing alone. It may be regarded as a motor deficit of visual tracking, which indicates that the first step in the transformation of a purely visual signal into a motor signal may take place in the MST.

The MST and the posterolateral part of area 7a (PP) seem to have some physiological properties in common. This is true particularly for visual-tracking neurons, which respond more strongly to smooth pursuit against a light background than in the dark (Kawano et al. 1984; Sakata et al. 1983).

Finally, another cortical area involved in smooth pursuit is the FEF. Pursuit-related neurons have been identified deep within the arcuate sulcus. They respond to foveal smooth pursuit or to the slow phase of OKN in a preferred direction and exhibit steady activation

during fixation of gaze in preferred eccentric positions.

In the infratentorial compartment, various pontine nuclei, such as the dorsolateral pontine nuclei (DLPN) and the nucleus prepositus hypoglossi (PH), are involved in smooth-pursuit eye movements (Eckmiller 1987).

Cortical projections to the paramedian tegmental nuclei have also been demonstrated. Of particular clinical interest are cerebellar structures such as the flocculus, the parafloccculus and the posterior vermis. Lesions involving the flocculus and the parafloccculus in adult macaques abolish the ability to hold gaze in eccentric positions and impair smooth-pursuit eye movements.

Unfortunately, the complex organization of smooth pursuit has not yet been elucidated despite an abundant body of data from anatomical, lesion, stimulation and single-unit studies. A first draft of the motor program may be generated in the FEF, which receives information from various structures. Thus, a serial transformation from visual information to a motor program could be established along a set of different cerebral structures, e.g. from the LGN to V 1 to the MT to the MST and PP and finally to the FEF (Eckmiller 1987; Tusa and Ungerleider 1988). On the other hand, direct connections from the MT and MST to the DLPN have been identified, and a direct access has even been found from V 1 to the pontine nuclei. Thus, smooth pursuit may not be organized only in a serial set, but may also use parallel channels. To make it even more complex, various inherent feedback mechanisms may constitute separate circuits superimposed on the main channels.

Even less information is available on the site and mechanism for achieving such complicated activities as target selection, inspection, search and anticipation. As mentioned earlier, moving-pattern recognition seems to first be established in the MT.

But what structures determine the target of gaze? A commonly held view is that the forebrain is responsible. One of the structures suggested as a central controller is the intermediate layer of the central thalamus (IML), which receives information from various infratentorial and cortical areas. Conversely, neurons of the IML project to several cortical areas, including the FEF, the inferior parietal lobe, the anterior cingulate cortex and most visual areas (Schlag and Schlag-Rey 1984, 1986; Schlag-Rey and Schlag 1984). The IML therefore seems to be ideally suited for such complex control functions. However, this still remains an interesting but unproven hypothesis.

Destruction of the IML and pulvinar have resulted in a syndrome of contralateral visual neglect (Orem et al. 1973; Watson and Heilmann 1979; Zihl and von Cramon 1979). Two possibilities are being considered to explain the pathophysiology of visual hemineglect. One is that a lesion of the IML or its cortical connections may abolish thalamic control of gaze strategies.

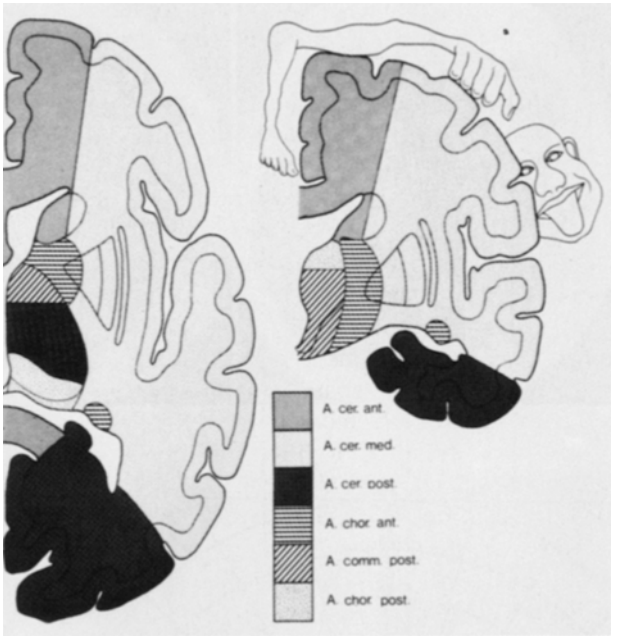

Fig. 3. Areas of supply of cerebral vessels (from Marx 1977)

A second hypothesis would add a completely new dimension to the problem of smooth pursuit and saccadic eye movements. According to Watson et al. (1974), destruction of the mesencephalic reticular formation induces multimodal unilateral neglect. It might therefore be suggested that a cortico-limbic-reticular activating loop is interrupted by the thalamic lesion and that the neglect syndrome reflects an attention-arousal defect rather than a direct defect in visual motor control. Both hypotheses are in good agreement with a recent study of Bogousslavsky et al. (1988), who showed that an infarction of the retrolenticular portion of the internal capsule and the white matter of the temporal isthmus resulted in a hemineglect syndrome in man.

The second part of this article deals with some cerebral ischaemic infarctions that have led to oculomotor dysfunctions. Figure 3 shows supply areas of cerebral vessels (Marx 1977). As can easily be seen, the occipital visual areas are supplied by the posterior cerebral artery. The MT, the MST, the PP and the FEF are mostly supplied by the middle cerebral artery or lie in the border zone of the anterior and middle cerebral arteries.

A deep infraction in the area of the posterior and adjacent middle cerebral artery (Fig. 4) was accompanied by a homonymous hemianopia, an abolition of visually guided purposeful saccades to the contralat-

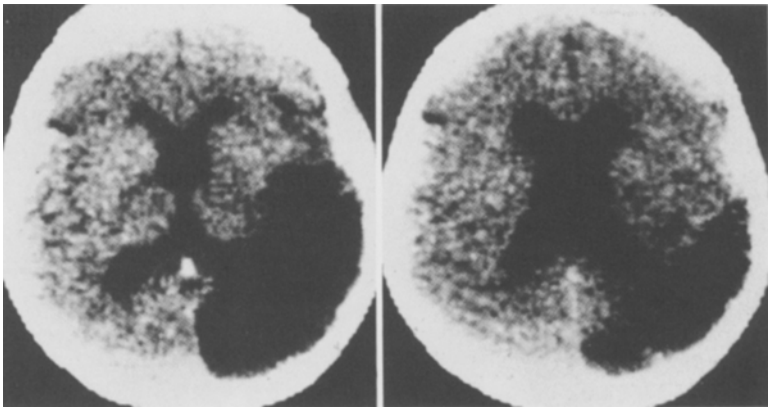

Fig. 4. Parieto-occipital brain infarction

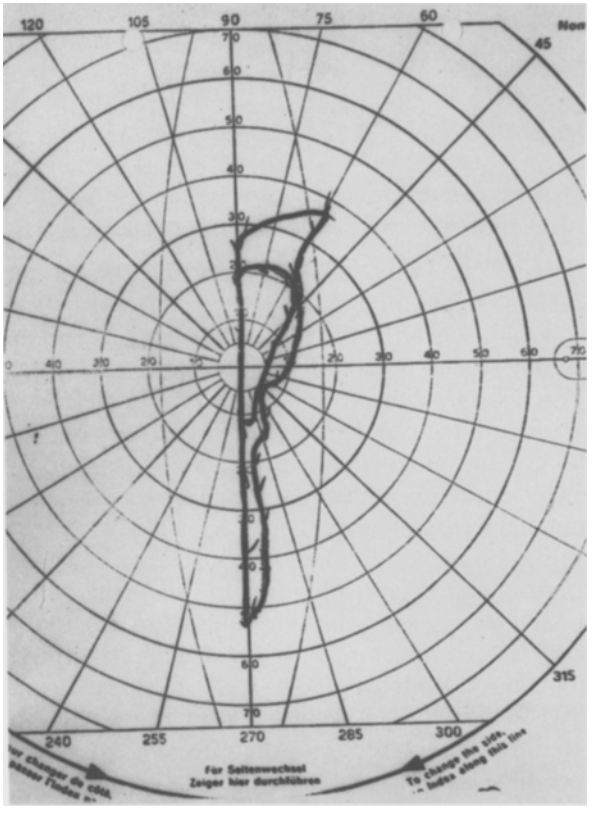

Fig. 5. Remaining visual field in a patient suffering from a bilateral occipital infarction

eral side and a disturbance of smooth pursuit to the affected side. After suffering a bilateral occipital infarction, another patient (Fig. 5) was unable to perform visually guided saccades as well as smooth pursuit, but the ocular cephalic reflex remained unimpaired. He was likewise able to saccade towards auditory targets, spontaneous saccades also being preserved.

Recently, Thurston and co-workers (1988) presented a very elaborate study in patients suffering from unilateral lesions of the cerebral cortex. Most of the patients had a smooth-pursuit asymmetry while tracking predictable target motion to the affected side, as shown by a diminished smooth-pursuit gain adjusted by corrective saccades. The smooth-pursuit deficit was independent of homonymous hemianopia, indicating that lesions in the temporal, parietal and frontal cortex affect smooth pursuit even in the presence of undisturbed occipital functions.

In a second examination, the authors used step ramp stimuli in different directions, which were stepped in a pseudorandom sequence into the right or left visual hemifield. This paradigm therefore did not check foveal pursuit but allowed documentation of pursuit and saccadic eye movements which were elicited only from visual half-field stimulation. In patients who had a smooth-pursuit deficit to predictable target motion and intact visual fields to the target stimulus, presaccadic eye velocity was diminished or even abolished in all movements to the side ipsilateral to the lesion, but not to the contralateral side. This indicates a unidirectional tracking deficit to the ipsilateral side regardless of whether the stimulus is introduced into the right or left visual hemifield. This finding corresponds to that obtained in connection with the MST lesion in monkeys. These patients likewise showed a bidirectional tracking deficit in response to moving stimuli presented in the visual hemifield contralateral to the side of the lesion, although none of them displayed a visual-field defect to the target stimulus. Accordingly, all these patients effected inaccurate saccades to the moving target, obviously indicating an inability to judge the speed of the target in the hemifield. This finding is in good agreement with aforementioned experimental evidence in monkeys with small chemical lesions in the MT.

As might be expected, the lesions in the investigated patients varied in size as well as in the extent of involvement of underlying white matter. Therefore in this study it was not possible to identify with certainty the homologues of the MT and MST in man and their projections.

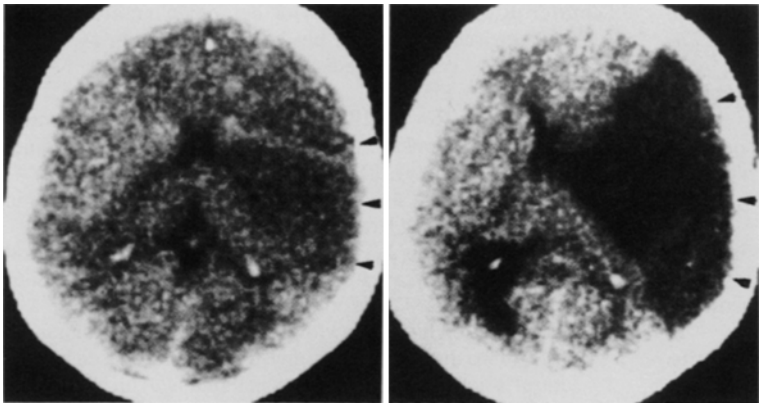

Fig. 6. Deep hemispherical infarction. *Left:* early phase; *right:* after 2 weeks

In deep hemisphere infarctions (Fig. 6) involving the perforating branches of the middle cerebral artery, a tonic deviation of both eyes to the side of the affected cerebral hemisphere can be observed, which is due to tonic impulses from the unaffected hemisphere. Since the accompanying hemiplegia involves the contralateral side, these patients look away from their paralytic extremities. Tonic eye deviation is an indicator of a poor prognosis. However, if the patient survives, tonic deviation usually subsides after some days. A persistent gaze paralysis to the contralateral side only occurs in lesions with interruption of both the occipitotectal and frontopontine projections (Pasik and Pasik 1975).

Patients with deep hemisphere infarctions often present with a homolateral Horner's syndrome which is due to an involvement of the diencephalic sympathetic center (Schiffter and Schliack 1974).

Infarctions in the territory of the anterior choroidal artery affect the retrolenticular portion of the internal capsule. The main resultant defect is a hemineglect syndrome on the contralateral side (Bogouslavsky et al. 1988). Such a patient did not respond to a verbal command given from the left side, omitted the first three or four words of the line when reading or writing, and recognized sensory stimuli applied simultaneously on both sides only on the unaffected side homolateral to the lesion. Although there was no involvement of cortical structures, the EEG and cerebral blood flow were slowed over the affected hemisphere. This finding might be interpreted as the result of a disruption of a loop of the cortical-limbic-reticular formation that regulates visual and sensory attention.

Another possible influence exerted on the visual system by the reticular formation of the brain stem might be deduced from the rare finding of vivid hallucinations in Weber's syndrome (paramedian midbrain infarction), which has been interpreted as a release of stored visual material due to reticular-formation involvement (Geller and Bellur 1987).

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Received Oktober 27, 1988