Short Communications

Unit activity in the pontine reticular formation associated with eye movements

A number of lines of evidence suggest that saccades and quick phases of nystagmus in the horizontal plane are generated in the pontine reticular formation[2–4,6–8,13,18]. For this reason unit activity in this region is of considerable interest. Duensing and Schaefer[9,10] were the first to record from units in the reticular formation of the rabbit. They found some units which exhibited predictable and regular activity patterns during quick eye movements. Other units were only 'loosely-coupled' to eye movements. Units associated with quick phases of nystagmus in a particular direction were located on both sides of the brain stem.

Unit activity in the reticular formation and in the region of the oculomotor nucleus has also been found in the cat[21], goldfish[16], and monkey[12,19]. There are a number of differences in results in these studies, some of which could be due to variations in the visual axis and binocular fields in these animals, or to different recording locations. The purpose of this report is to give a qualitative description of units in the paramedian zone of the pontine reticular formation (PPRF) of the alert monkey. A preliminary report appeared earlier[14].

Experiments were done on alert juvenile rhesus monkeys (*Macaca mulatta*). They moved their eyes spontaneously, or vestibular or optokinetic nystagmus was induced. Tungsten microelectrodes of 3–10 MΩ were moved into the pontine reticular formation with a hydraulic microdrive through a plug permanently implanted on the skull. Vertical and horizontal eye movements were recorded with platinum needle electrodes using DC-coupling. EOG and unit data were stored on FM magnetic tape. At the conclusion of experiments, lesions were made above and below regions of interest and electrode locations were identified in histological sections. Details of recording techniques and of methods used for calibrating the EOG are given in previous papers[1,15,17]. Preliminary analysis was done with a frequency meter which gave a pulse at the time of occurrence of a spike whose voltage was proportional to the reciprocal of the preceding interspike interval.

Unit activity associated with eye movement described in this report was recorded in rostral parts of the PPRF. The PPRF lies caudal to the oculomotor and trochlear nuclei and rostral to the abducens nucleus[8,13]. It occupies medial portions of nucleus reticularis magnocellularis between 0.5 and 2 mm from the midline on either side of the pons. In the reticular formation adjacent to the PPRF there was little or no activity associated with eye movement. Inside it almost every unit was related to eye movement in some way. Many units were identified as cells by an A–B break in the action potentials. Unit activity in caudal parts of the PPRF which are contiguous with the abducens nuclei will be the subject of a separate report.

Recordings were of sufficient quality and duration (between 20 sec and 100 min)

TABLE I

ASSOCIATION OF EYE MOVEMENTS AND UNIT ACTIVITY

Parameters associated with eye movement	*Burst units*	*Pause units*	*Total*
Frequency changes with all rapid eye movements	13	12	25
Frequency changes with all rapid eye movements, but some directional sensitivity	26	3	29
Frequency changes with all rapid eye movements; inter-pause frequency related to eye position	—	5	5
Frequency changes with rapid eye movements; some directional sensitivity; also related to eye position	9	1	10
Occurrence of blinks only	2	—	2
Others	—	—	15
Total			86

for analysis in 86 units. About one-third of the units were tested during vestibular or optokinetic nystagmus as well as during periods of fixation. Unit responded in a fixed and predictable fashion only when the monkeys were alert. During drowsiness or sleep, units fired irregularly at low rates, but they resumed their regular activity when animals were aroused. Recordings used for characterizing unit activity or for quantitative analysis were taken while animals were alert.

The units were separated into 3 groups. These groups are listed in Table I and are described in more detail below.

Burst units. These units fired with a burst of spikes before and during quick eye movements (Fig. 1, Fig. 2A, B). Their activity was similar during all rapid eye movements, including saccades or quick phases of vestibular or optokinetic nystagmus (Fig. 1E, F). Burst units also had activity changes before and during blinks, whether or not there was an associated horizontal movement of the eyes (Fig. 1C, Fig. 2B). In most units the latency between onset of the burst and onset of eye movement was between 12 and 20 msec (Fig. 1A–C). In other units the increase in frequency occurred at longer latency before the onset of eye movements (Fig. 1D–F). The latency to onset of eye movement was short in a few units (Fig. 2B), or the units fired after the onset of eye movement.

Some burst units were directionally insensitive and the latency and number of spikes was approximately the same for rapid eye movements of the same size in any direction (Fig. 1C; Fig. 2A, B). Others had differences in activity when the eyes moved in a particular direction. For example, the neuron shown in Fig. 1A, B, fired earlier and with more spikes when the eyes moved to the left than to the right. The directional sensitivity of PPRF units when it was present was mainly, but not exclusively, in the horizontal plane. It was usually not as strong in pontine units as in motoneurons, since there was often also some activity when the eyes moved into the off-direction. Burst units which fired maximally or exclusively during eye movements in one direction were found on both sides of the pons.

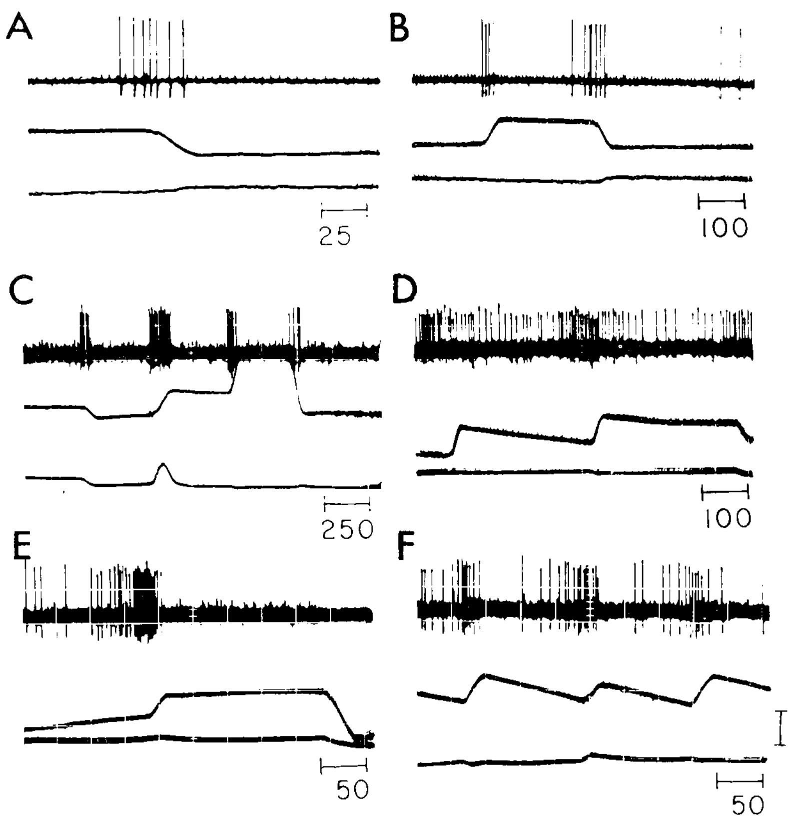

Fig. 1. Burst units. Top trace, unit recording; middle trace, horizontal EOG; bottom trace, vertical EOG. Eye movements to the right and up caused upward trace deflections in the horizontal and vertical EOG, respectively. The time base (msec) is shown below. The vertical bar beside F shows 25° of deviation for each of the EOG traces. A and B, Burst unit which fired earlier and with more spikes when the eyes moved to the left than to the right. C, Multi-directional burst unit which had no spontaneous activity during periods of fixation or slow eye movements. The burst began 12–20 msec before the onset of eye movement. Note the intense activity which accompanied a blink (upward deflection, bottom trace). D, Multi-directional burst unit firing 50–100 msec before the onset of eye movement. E and F, Directionally sensitive unit which fired 50–100 msec before the onset of saccades (E) or quick phases of nystagmus (F) to the right. The unit did not fire before eye movements to the left. The time base is in msec in Figs. 1 and 2.

In most units without directional sensitivity, maximum frequencies tended to be the same during each burst (Fig. 2A). However, the duration of firing was positively related to the duration of eye movements, being longer for larger eye movements. A similar relationship was often present in units with directional sensitivity as well.

In some units there was little or no activity during slow eye movements or periods of fixation (Fig. 1A–C). In others such activity was present but was unrelated to eye position (Fig. 1D, Fig. 2B). The frequency of firing between bursts could be related to eye position in a few neurons, but the relationship was never as close as in motoneurons[15].

Pause units. Pause units exhibited continuous firing which stopped before and

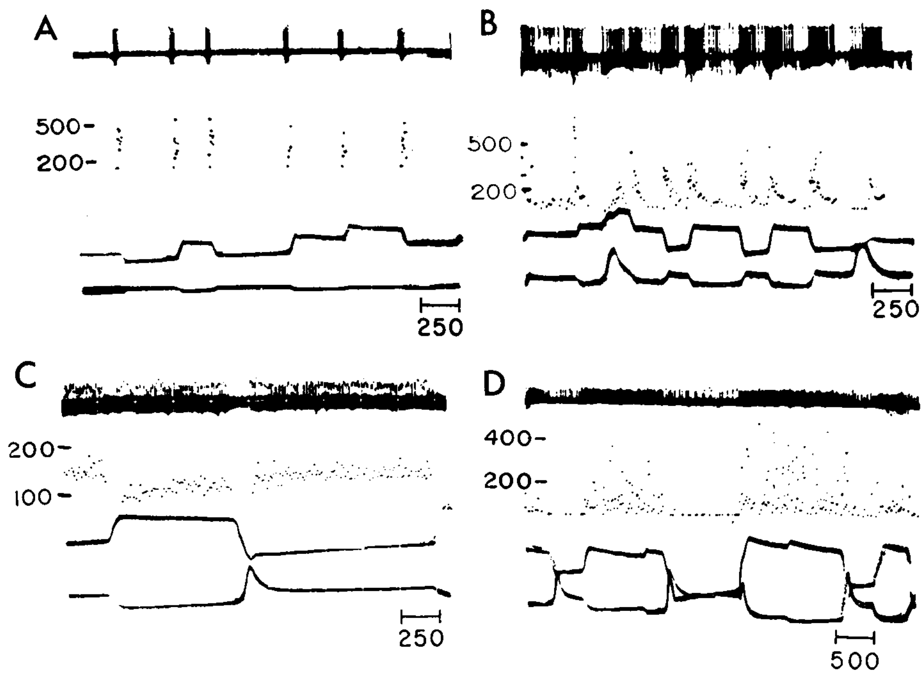

Fig. 2. Top trace, unit recording; 2nd trace, dot display showing the instantaneous frequency of unit activity. Each display is calibrated in impulses/sec. The 3rd and 4th traces are the horizontal and vertical EOG, respectively. The time base (msec) is shown below. The vertical bar beside D shows 25° of deviation for the EOG traces. A and B, Multi-directional burst units. The peak frequency of these units was approximately the same during all eye movements. The unit in A fired 12–20 msec before the onset of eye movement. In B the increase in frequency began slightly before the eyes began to move, and the peak frequency occurred during eye movement. C, Unit which paused during eye movements in all directions. The inter-pause frequency was higher when the eyes were to the left and up. D, Unit which fired more when the eyes were on the right than on the left.

during quick eye movements and blinks (Fig. 2C, Fig. 3). The units paused similarly during all rapid eye movements independent of whether they were saccades (Fig. 3A, C, D) or quick phases of optokinetic or vestibular nystagmus (Fig. 3B). Latency between beginning of the pause and beginning of the quick eye movement was between 12 and 20 msec (Fig. 3C). Latencies tended to be somewhat shorter for smaller than for larger eye movements. The pause units resumed firing just at the end of eye movement, the initial intervals being slightly longer than succeeding intervals (Fig. 3). Otherwise, activity in pause units was very regular (Fig. 2C, Fig. 3), much more so than the irregular firing frequently found in burst units.

The duration of the pause was positively related to the amplitude and duration of eye movement by a power function, $Y = 0.004X^2$, in which X is duration of the pause in msec and Y is the amplitude of eye movement in degrees[6]. This relationship was found for each of several pause units which were studied, including those shown in Fig. 3A–C and D. It was also found for several pause units located in the region of the motor nuclei.

A small percentage of pause units stopped firing only during horizontal eye

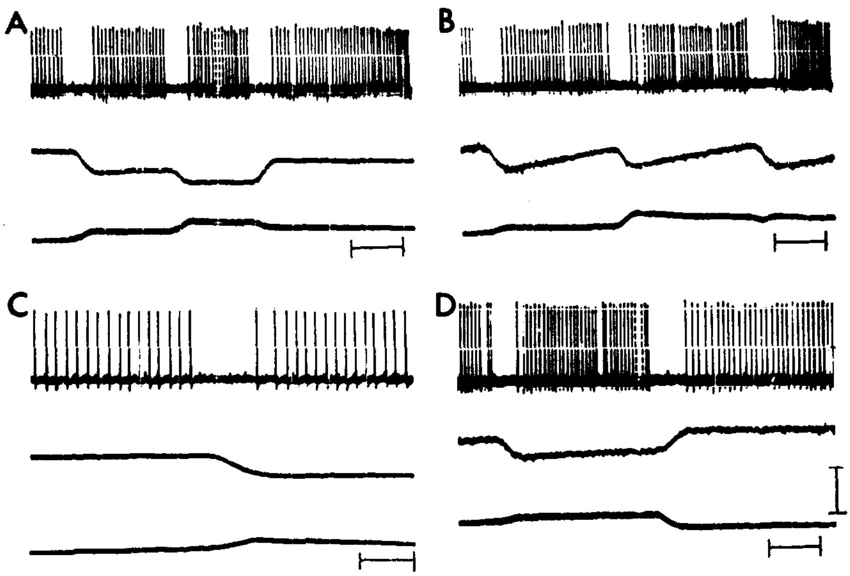

Fig. 3. Pause units. Scheme as in Fig. 1. A–C, Unit in which the inter-pause frequency was relatively constant. Note that the unit had a similar cessation of activity during saccades (A, C) or quick phases of nystagmus (B). D, Pause unit whose inter-pause frequency was higher when the eyes were up and to the left. The time calibrations are 100 msec for A, B and D, and 25 msec for C. The vertical bar beside D shows 25° of deviation for the horizontal and vertical EOG in each of the traces.

movements in a particular direction. Most pause units had no change in frequency during periods of fixation or slow eye movements, but, activity in some neurons was related to the position of the eyes. For example, the neurons shown in Figs. 2C and 3D fired at higher frequencies when the eyes were to the left and up. However, the relationship between frequency and eye position was never as close as in motoneurons[15].

Other units. In addition to burst and pause units, other types of units were found in the PPRF whose activity was more complex and was not as easily classifiable. Most of these units were related to quick eye movements in some way. However, latencies varied or units would fire only to a certain percentage of movement in all or in certain directions. Such units were tabulated only when several min of continuous recording showed that the relation between frequency change and the occurrence of eye movement was well above chance. Examples of complex units are shown in Fig. 1D and Fig. 2B, D. One unit fired more rapidly before eye movement in any direction (Fig. 1D), but only for about 80% of movements. In several units the firing rate was related to the position of the eyes in one hemifield. The unit shown in Fig. 2D fired infrequently during eye positions on the left, but was more active in an irregular fashion when the eyes were on the right. Two neurons only fired before blinks, but had no activity before other quick eye movements. With a more extensive sample of neurons other types of units will undoubtedly be found.

Many of the action potentials in the region of the pontine reticular formation had A–B breaks, were negative-going, and were held for considerable periods of time.

This suggests that the recording electrodes were near the somata of neurons. This is consistent with the hypothesis that oculomotor function is represented in activity of cells in medial portions of nucleus reticularis magnocellularis[2,3,6,18]. Activity associated with eye movement has also been found in this region in other unit studies[9,10,12,21].

PPRF unit activity and gross potential changes associated with eye movements in this region[4] were similar in a number of respects:

1. Frequency changes in units or gross potential changes generally occurred between 12 and 20 msec before the onset of quick eye movements.

2. Most neurons had a frequency change before all eye movements. However, some units changed their activity preferentially before quick eye movements in a particular direction. These directions were usually predominantly horizontal. PPRF potential changes occurred before and during all eye movements, but tended to be larger and more complex when the eyes moved to the ipsilateral side.

3. Changes in unit activity and gross potential changes were the same regardless of whether quick eye movements were saccades or quick phases of vestibular or optokinetic nystagmus. This supports the contention that saccades and quick phases of nystagmus are generated by a common neural mechanism and are similar regardless of whether they are induced by the visual or vestibular systems[6].

4. Blinks were also associated with activity changes in units and with gross potential changes in the PPRF. Changes in activity of units during blinks resembled those during large quick eye movements. Blinks are also associated with potential changes in LGB[11] and the calcarine cortex[5].

5. Some units exhibited activity during positions of fixation, but in none of the units were there the same relationships between frequency and positions of fixation as in motoneurons[15]. Similarly, gross potential changes did not occur during slow eye movements and positions of fixation.

As noted, it has been shown that the PPRF plays an important role in producing eye movements and periods of fixation in the horizontal plane[3]. It is the most peripheral portion of the oculomotor system where conjugate horizontal eye movements are induced or affected by stimulation or lesions[2]. All types of horizontal eye movements and positions of fixation are induced by PPRF stimulation[7]. Moreover, deviations induced by PPRF stimulation tend to be of constant velocity and within limits their size is proportional to the number of pulses used for stimulation. From this it has been inferred that there is integration of neural activity in the PPRF or in the relay between the PPRF and the eye muscle motor nuclei[7].

The latency of the PPRF-induced deviations is short, and no more than one or two synapses separate it from the eye muscle motor nuclei[7]. Anatomical pathways between the PPRF and the motor nuclei have not been firmly established yet, but it is clear from stimulation studies that they exist. Lesions of the PPRF cause profound paralysis of conjugate horizontal gaze[2,8,13,20]. Particularly striking are the abolition of quick eye movements to the ipsilateral side, and the inability to attain eye positions in the ipsilateral hemifield[3,8].

Despite the findings of lesion and stimulation studies, it is clear from the unit studies that eye movement is mainly represented in the activity of PPRF neurons, and that frequencies responsible for holding the eyes steady are generated elsewhere. We have recently shown that phasic changes in firing of motoneurons during saccades and tonic activity during subsequent positions of fixation are most closely related to a single parameter: change in eye position[15]. This suggests that activity responsible for the tonic and phasic responses of motoneurons arises from a common source. It indicates that a single vector in central structures representing direction of eye movement and amplitude or duration could contain the information necessary to generate saccades and subsequent positions of fixation. As shown in the present study, this information is represented in activity of various types of units in the PPRF.

On the other hand, activity more closely related to positions of fixation is much more prominent in units in and around the motor nuclei (see refs. 12 and 15; also Henn and Cohen, unpublished data). Moreover, burst and pause units have also been found in the region of the motor nuclei at latencies which were approximately the same as in the PPRF[6,16,19]. Taken together, these studies suggest that PPRF neurons induce quick eye movements in the horizontal plane by integrating activity from a variety of sources, and projecting it to the appropriate eye muscle motor nuclei. If correct, then tonic activity of motoneurons is locally determined, and neural organizations in and around the motor nuclei are of major importance in producing the overall tonic and phasic responses of motoneurons.

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