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Purkinje Cells in the Cerebellum: Their Responses to Postural Stimuli in Cats*

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Abstract. The responses of Purkinje cells in the cerebellum produced by various positions of the limbs were studied in decerebrated unanesthetized cats. The majority of units located in the intermediate zone of the anterior lobe selectively reacted to definite postures of the limbs: some of them were active when a given limb was in an extended position and were silent when it was in flexion; the other ones, on the contrary, were active when the limb was flexed and silent when it was extended. The rate of discharges was in both cases the same and amounted to 40 to 80 per second. It did not change with the lapse of time, and remained the same when flaxedil was administered. These results, in connection with some other data, seem to explain the problem of how the cerebellum transforms the information about the tensions of tendons and muscles, delivered by the tendon organs and muscle spindles, respectively, into the information about movements.

The significance of Purkinje cells as units receiving messages from the receptive surfaces of the body is so far poorly understood. Whereas it is known that the cerebellar neurons, in general, react readily to postural, tactile, and painful stimuli from various locations,[1–6] the responses of Purkinje cells have not been systematically investigated. Only Thach[7] in his study on freely moving monkeys obtained records from Purkinje cells during the performance of motor acts. The present paper is concerned with the problem of the effects on Purkinje cells of passive displacements of limbs, particularly joints, further denoted as "passive movements." The effects of other manipulations, like squeezing or stroking, will be presented elsewhere.[8]

Material and Methods. The experiments were performed in ten cats. In the first stage, under Nembutal anesthesia (35 mg/kg), bilateral craniotomy was made, the falx cerebri divided between ligatures, the carotid arteries were clamped for 10 to 15 min, the brainstem was cut at the precollicular level by means of stereotaxic procedure, and the cerebral hemispheres were removed. Thereafter, the anterior folia of the cerebellum were widely exposed on the right side and the operation field was covered with 1.5% agar-agar in Ringer's solution. The rectal temperature was maintained at 38 ± 1°C. The arterial pressure was at the level of 100 to 120 mm/Hg. The experiments began at least 6 hr after surgery.

The details of the recording techniques will be given elsewhere.[8] The discharges from Purkinje cells were recorded extracellularly by tungsten microelectrodes or micropipettes filled with 2 *M* KCl. The cells were identified by the following features: (*a*) high voltage

and regular spike series with constant amplitude and frequency, with "complex spikes" interposed;[7, 9] (*b*) the histological control of the location of the electrodes by marking.[10]

Since our preparations were relatively flaccid, all our manipulations with the limbs (made by hand) encountered weak resistance. Forelimbs were flexed and extended in finger joints, wrist, elbow, and shoulder, the passive movements of the hind limbs concerned toes, ankle, knee, and hip. All the displacements of the limbs were static, they lasted many seconds, or even a few minutes.

Results. Since penetrations into the cerebellum were made near the edge of the folium, it was possible to move the electrode parallely to the wall of the sulcus along the Purkinje layer. Thus with one successful penetration we could encounter about ten Purkinje cells. Altogether in ten cats we made 52 penetrations in the intermediate zone of the anterior lobe and examined the activity of 301 Purkinje cells.

All units we have examined could be divided into those which were active without any external manipulations, with a regular discharge rate of 40 to 80 per second (133 units), and those which in this condition discharged very poorly (a few discharges per sec), or were completely silent (168 units). Among spontaneously active units, 42 did not react to any of our manipulations. The remaining 91 units reacted to passive flexion of at least one joint. In the majority of instances the response consisted in complete abolition of the discharges; the unit was silent during the whole period of flexion (which could last for a number of minutes), and resumed its activity with the usual rate immediately after the cessation of flexion (Fig. 1). Only rarely did the given unit react to passive flexion by acceleration of discharges.

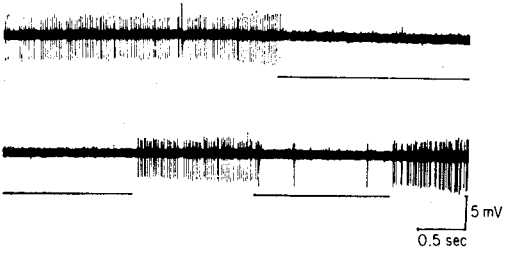

FIG. 1.—Silencing of "spontaneously" discharging Purkinje cell by passive elbow flexion of the ipsilateral foreleg. The line below the record denotes the period of flexion.

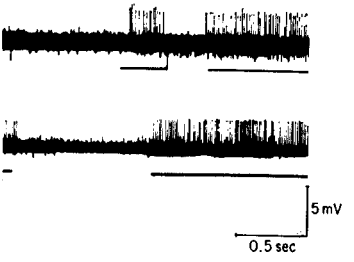

FIG. 2.—Discharging of silent Purkinje cell to passive flexion of the knee (denoted by lines below the record).

Among the silent or poorly active units, 140 reacted to passive flexion of at least one joint. The response consisted in discharging with the rate of 40 to 80 per second and lasted as long as the limb was flexed. As soon as flexion was discontinued, the unit again became silent (Fig. 2). The behavior of such unit during flexion did not differ in any way from that observed in "spontaneously" active unit.

In some preparations, when a unit reacted in a consistent way, flaxedil (1 ml/hr) was administered. This did not change the responses of the cell in any appreciable way.

In a few cases Novocain (2%) was administered into the joint which was subjected to flexion. This measure also failed to influence the responding of the Purkinje cells.

Of all units reacting to passive displacements of limbs, some reacted to passive movements of one joint only, others reacted to passive movements of two adjacent joints, others reacted to passive movements of two symmetrical joints, and still others reacted not only to passive movements but also to other manipulations. The detailed analysis of all these combinations is presented elsewhere.[8] Here we shall note only that: (*a*) on the average, much more units reacted to ipsilateral (in respect to the cerebellar hemisphere) passive movements than to contralateral movements; (*b*) the number of units reacting to passive movements of forelegs and hind legs was nearly equal; and (*c*) among the units reacting to passive movements of the foreleg prevailed those whose responses were ipsilateral and limited to one or two joints, whereas among the units reacting to passive movements of the hind legs, the majority reacted to bilateral hip and knee flexion. Finally, it should be noticed that passive extension of the limb beyond its semiextended position which was maintained at rest very rarely produced a response.

Discussion. In another paper[8] it will be shown that only the static postures of the limbs produced regular effects in the Purkinje cells in our experiments, whereas squeezing of a limb producing often a slight flexor reflex gave rise to less reliable and irregular phasic responses, and stroking of the skin gave responses in a few cases only. Since spontaneously active units, when the limbs are in a semiextended position, stop their activity immediately and for an indefinite period when one limb is passively flexed, it may be concluded that these units, in fact, *react* to the extended position of the limb precisely in the same manner as the spontaneously silent units react to passive flexion. In other words, Purkinje cells always react excitatorily either to the extensor posture of the limb or to its flexor posture. The fact that administration of flaxedil producing complete immobilization of the animal does not change these responses indicates that here we are concerned with purely postural phenomena without participation of a myotatic reflex.

Passive flexion or extension of the leg involves activation of: (1) Golgi tendon organs and spindle afferents of the muscles antagonistic to the position of the limb (that is of extensors when the limb is in flexion and vice versa) and (2) articular receptors corresponding to a given position. Since injection of Novocain into the joints concerned did not change the reactivity of the Purkinje cells, we may conclude that these cells react either to the discharges from spindles, or from tendon organs, or from both. This point will be discussed below.

In a recent monograph, one of the authors[11] drew attention to the fact that the cerebellum may be regarded as a sort of "convertor" transforming the messages concerning *stretching* of tendons and muscles, detected by tendon organs and spindles, respectively, into the messages informing about *movements*. The problem of what is the mechanism of this transformation has been so far unexplained. It seems, however, that the results described in this paper, combined with those obtained by other authors, throw some light upon this problem.

Let us consider the following facts: (1) In the early 1930's Matthews[12] discovered that contraction of a moderately stretched muscle produces an increase of discharges from Golgi tendon organs and a dramatic decrease of discharges from spindles. This is due to the fact that spindles are situated "in parallel" with the muscle fibers, and, therefore, are inactivated when the muscle is shortened.[13]

(2) A few years ago, Ito and his associates (cf. Eccles *et al.*[14]) showed that the neurons of the intracerebellar nuclei, so far considered to be the relay stations for the efferent impulses from the cerebellum to the cerebral cortex, are not excited but strongly *inhibited* by impulses conveyed to them by axons of Purkinje cells.

(3) Accordingly, the problem arose as to what is the source of excitatory impulses going to the intracerebellar nuclei. On the basis of both anatomical and physiological evidence[14] it was concluded that many afferent fibers to the cerebellum, among them those running in the spinocerebellar tracts, send collaterals to the intracerebellar nuclei conveying excitatory impulses to them. To sum up, the neurons of those nuclei are bombarded by both inhibitory impulses delivered by Purkinje cells and by excitatory impulses conveyed directly through spinocerebellar tracts.

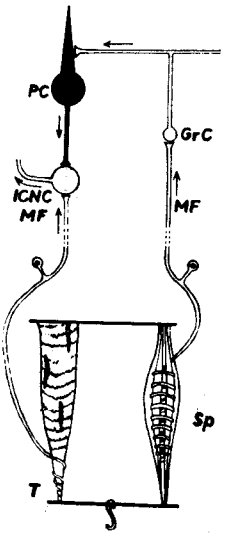

FIG. 3.—The supposed mechanism of the function of the cerebellum. PC, Purkinje cell; GrC, granule cell; MF, mossy-fibers; ICNC, intracerebellar nuclear cell; T, Golgi tendon organ; Sp, muscle spindle. Inhibitory neuron drawn in black, excitatory neuron drawn in white. Explanations in text. The upper part of the figure is modified from Eccles *et al.*;[14] lower part is modified from Fulton and Pi-Suner.[13]

Now, we propose a hypothesis according to which the messages running from spindles impinge only (or mainly) upon Purkinje cells, whereas messages running from tendon organs reach intracerebellar nuclei directly (Fig. 3). Let us see now what will be the result of this arrangement.

If a given muscle is passively stretched, as is the case with extensors when the limb is flexed, or with flexors when the limb is extended, and no myotatic reflexes are in operation, then both the tendon organs and muscle spindles are activated. In effect the excitatory impulses impinging on neurons of the intracerebellar nuclei from tendon organs are counterbalanced by inhibitory impulses impinging upon them from Purkinje cells excited by muscle spindles. Thus, information about passive movements, for instance flexion of the leg, cannot be conveyed to the intracerebellar nuclei, and hence to the cerebral cortex, because relaxed flexor muscles activate neither tendon organs, nor spindles, and stretched extensors activate both of them.

If, however, a muscle is actively contracted against some resistance, as is the case when the animal performs a normal motor act, then the tendon organs will be

strongly activated, but the spindles will be silenced. (The role of γ efferents is neglected for the sake of simplicity.) In effect, the neurons of the intracerebellar nuclei will be excited, and their excitation will be the stronger, the stronger the tension of the tendon organs and the stronger the contraction of the muscle.

Since the preponderance of the discharges from tendon organs over those from spindles exists only when the muscle is actively contracted against resistance, it follows that excitation of intracerebellar nuclei is directly related to active motor acts. It may be added that pure isotonic contractions without resistance (when, for instance, the tendon is cut) also fails to activate the intracerebellar nuclei, since then the tendon organs are not activated.

Thus we come to the conclusion that the intracerebellar nuclei are activated only when the active movements against resistance are performed, and that information about these movements is conveyed to higher centers of the brain and finally to the motor cortex. The role of the Purkinje cells is to prevent the messages from the spindles from reaching the intracerebellar nuclei, and thus to discriminate between the stimulus patterns produced by passive stretching of the muscles, and stimulus patterns produced by active movements against resistance. It may be assumed that the information about passive stretching of the muscles is conveyed to the brain by spino-bulbo-thalamic tracts discovered by Oscarsson and Rosen,[15] that is, through the same pathways which convey the information from joint receptors. Thus the passive aspects of proprioception, namely, stretching of muscles and positions of joints, are conveyed to the cerebral cortex by spino-cerebral pathways, whereas active aspects involved in movements are conveyed through spino-cerebello-cerebral pathways.

To end these considerations we may ask why the messages from movements do impinge upon Purkinje cells, as shown by Thach[7] and also in our own experiments.[8] We suppose that these messages arrive at Purkinje cells not from the contracting muscles, but from antagonistic muscles which are stretched during the performance of the movement.

Although the experiments concerning the direct verification of this hypothesis are in progress we have decided to present it now, because it implies a great number of experiments which may be done in other laboratories, and the question it tries to answer seems to be an important one.

Note added in proof: According to the recent data obtained by Eccles, *et al.* (*Brain Research*, **14**, 222 (1969)), Oscarsson (private communication), and Tarnecki (unpublished), group II afferents convey impulses to the Purkinje cells, whereas group I afferents virtually fail to do so. As is well known, group II afferents innervate secondary spindle endings activated mainly by *static* stretches of the muscles. On the other hand, group I afferents innervate primary spindle endings, activated by the dynamic stretches of the muscles, and tendon organs (cf. Matthews, P.B.C., *Physiol. Rev.*, **44**, 219 (1964)). Tarnecki in his recent experiments (unpublished) has shown that group I afferents convey impulses to the units of the nucleus interpositus of the cerebellum, with very short latency. Accordingly, the pathway Sp-PC of Figure 3 concerns only group II afferents.

These data seem to confirm the essential aspects of our hypothesis, making it even more plausible. The fact that only secondary spindle endings send impulses to the Purkinje cells is in complete agreement with our data showing the *static character* of the responses of these cells. On the other hand, we have almost direct evidence to show that tendon organs send excitatory impulses directly to the nucleus interpositus, *quod erat ad demonstrandum.* The fact that primary spindle endings also send excitatory impulses directly to this nucleus does not in the least

undermine our thesis, except that it is not quite clear why it is so. Furthermore, in his pilot experiments Tarnecki has demonstrated that the increase of the strength of stimulation of the peripheral nerve 2, 5, and 7 times its threshold value (that is, activation of group II afferents) produces a dramatic inhibition of the cells of the interposite nucleus, inhibition appearing immediately *after* their excitation.

If these results are confirmed in further experiments, our hypothesis will receive additional proof.

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