Midbrain electrical fields produced by stimulation of the muscle branches of the oculomotor nerve

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Evoked potentials were recorded from the oculomotor nucleus in decerebrate cats following electrical stimulation of individual muscle branches of the oculomotor nerve. These potentials were usually triphasic but other more complex potentials were evoked depending on the positions of the recording electrode. Equipotential contour maps of the evoked electrical fields were plotted at different time intervals following the stimulation of the individual nerve branches. These maps provided a dynamic picture of the electrical field changes in the nucleus. Potentials evoked from individual extraocular muscles predominated in different regions of the nucleus. Potentials from the inferior rectus muscle predominated in the rostral homolateral part of the nucleus, from the medial rectus in the middle part of the nucleus, and from the inferior oblique in the most caudal part of the nucleus. Maximum evoked potentials from the superior rectus were obtained in the contralateral caudal part of the nucleus, but many potentials were also recorded from the homolateral middle and caudal parts. It, therefore, appeared reasonable to assume that the superior rectus muscle was bilaterally innervated. This assumption was further supported by retrograde degeneration studies in the oculomotor nucleus.

Synaptic transmission in the oculomotor nucleus of the rabbit was first studied by Lorente de Nó. Shimo-oku has reported physiological investigations of the evoked potentials within the oculomotor nucleus of the cat produced by stimulation of the branches of the oculomotor nerve. From these potentials contour maps were drawn of the electrical fields in the oculomotor nucleus. To our knowledge, the contour map method has been previously employed only for the study of spinal motor neurons. This paper presents a study of the electrical field changes in the oculomotor nucleus of the cat in the course of time following antidromic stimulation of individual muscle branches of the oculomotor nerve. The evoked potentials resulting from antidromic stimulation are described and used for the construction of equipotential contour maps. This technique may be of value in further studies of the primary reflex arcs involving the oculomotor nucleus. It may also provide a means of studying the supranuclear systems which, originating from the cerebral cortex, cerebellum, superior colliculus, and vestibular appara-
tus, modulate impulses within the oculomotor nucleus.

Methods

Experiments were performed on 20 cats, weighing between 2.5 and 3.0 kilograms. The anesthesia employed was intraperitoneal pentothal (30 mg. per kilogram). The surgical procedure consisted of a bilateral decerebration performed at the thalamo-collicular junction that eliminated impulses from the cortex and diencephalon. This procedure was followed by an orbitotomy. The roof of the right orbit was removed, exposing the eyeball and extraocular muscles. The insertions of the four muscles innervated by the oculomotor nerve—the medial rectus, superior rectus, inferior rectus, and inferior oblique—were ligated and severed from the globe. The lateral rectus and superior oblique muscles were also detached. The optic nerve was then ligated and severed, and the eye enucleated. Warm fluid paraffin was poured into the orbital cavity to prevent the tissues from drying. The branches of the oculomotor nerve were carefully dissected out on the inner sides of the extraocular muscle bellies. During the operation, the body temperature of the cat was kept between 37.5 and 39°C.

The stimulating electrode consisted of two Teflon-covered wires that were exposed only at the tip. The recording electrode was a sharp dental needle that was electrically polished in a solution of phosphoric and chromic acids which reduced the diameter of its tip from 5 to 10 μ. The recording electrode was insulated except at the tip.

The stimulating electrode was placed against the nerve branches of the oculomotor nerve and the recording electrode was inserted into the oculomotor nucleus with a stereotaxic device. An indifferent electrode was attached to the inner surface of the skull. The usual stimuli consisted of square-wave pulses of 0.01 msec, duration and an intensity of 10 volts. These parameters were varied slightly according to the thickness of the nerve branches to insure that a maximal response was obtained.

The recording electrode was left in place while the four peripheral oculomotor nerve branches were stimulated and then removed and reinserted at a new locus in the oculomotor nucleus. Reinsertions were kept to a minimum by this procedure, and excessive tissue damage was avoided.

The action potentials were displayed on a dual beam cathode ray oscilloscope (Tektronix, 502) and photographed. At the end of each experiment, a small lesion was made in the nucleus by applying direct current through the recording electrode. The animal was put to death painlessly and the brain examined histologically. The lesions served to identify the electrode tracts and the stimulated sites in the nucleus (Fig. 3).

Experimental results

Reference system for experiments. An imaginary fixed rectangular coordinate system was set up within the midbrain parenchyma according to the system devised by Snider and Niemer (10) (Fig. 1). The origin of the coordinate system was at the junction of three perpendicular planes: the midsagittal plane, the vertical interaural plane (located by the position of the ear plugs), and the horizontal plane (parallel with the horizon and located 10 mm. above the interaural line). The position of the recording electrode could, therefore, be identified by three coordinate points (Fig. 1).

1. Characteristics of the evoked potentials

![Fig. 1. Diagrammatic projection of the oculomotor nucleus and its adjacent structures on the midsagittal plane, after Snider and Niemer (10) (the autonomic nuclei are not included). NIII, oculomotor nucleus; NIV, trochlear nucleus; D, nucleus of Darkschewitsch; Rub, red nucleus; IPN, interpeduncular nucleus; MLF, medial longitudinal fasciculus. (From Snider, R. S., and Niemer, W. T.: A Stereotaxic Atlas of the Cat Brain, Chicago, 1961, The University of Chicago Press.)](image-url)
tials. The usual evoked potential had a triphasic configuration with a latency of 0.3 to 0.4 msec. (Fig. 2, A2.5 to 3.5, H-0.5, and A2.5 to 3.0, H-1). This configuration consisted of a positive deflection followed by a rapid negative wave and a slow positive wave. A slight notch was frequently seen on the ascending limb from the positive to the negative deflection of the wave. The magnitude and configuration of the triphasic wave was dependent on the distance of the recording electrode from the excited motoneurons. The modification of the wave appeared dependent on the anatomical arrangement of the axons, somas, and dendrites of the motoneurons and the transmitted impulses into structures that yield sinks and sources in a volume conductor. Detailed correlation between the configuration and the position of a recording electrode in the oculomotor nucleus of the rabbit have been described.\(^1\)\(^5\) In our experiments still other complex potential configurations were elicited by nerve branch stimulation. These potentials are characterized by complex configurations (Fig. 4, A) and by a second wave with a longer latency (Fig. 4, B).

2. Contour maps of the electrical fields. Antidromic evoked potentials were recorded from points in Fig. 1 and from points in parallel planes that were 0.5, 1, and 1.5 mm. distant from both sides of the midsagittal plane. The magnitudes of the evoked potentials were measured at 0.1 msec. intervals following the stimulus shocks. Maps were constructed by connecting points of equal potential at different time intervals after stimulation.

Fig. 5 shows a contour map constructed from the evoked potentials recorded from the midsagittal plane in a single experiment. At 0.5 msec. after the stimulus shock, all points from which electrical changes were recorded are positive, indicating that the impulses had not yet reached these points. At 0.8 msec., negative potentials were evident from the same points that
were positive at 0.5 msec. A negative potential field indicated that impulses had already been transmitted and excitation had taken place. The process of impulse transmission and neuronal excitation occurred simultaneously in any field, since positive and negative potentials were present simultaneously at certain time intervals after the stimulation. At 1.0 msec, all points showed negative potentials and centers of excitation were observed, i.e., localization of sinks. Between 1.0 and 1.2 msec, the negative potentials reached a maximum and then declined, occasionally producing transient positive changes. Thus, a map was constructed which dynamically represented in time the patterns of excitation in the oculomotor nucleus.

Fig. 6 shows contour maps obtained by stimulating the nerve to the superior rectus muscle and recording from parasagittal planes as well as from the midsagittal plane (same experiment as Fig. 5). Note that the middle map in Fig. 6 is the same as the third map from the left in the upper column of Fig. 5. Centers of excitation were noted caudally in all sagittal planes, but the center of maximum negativity was observed on the side contralateral to the stimulus.

When the nerve to the medial rectus muscle was stimulated, the centers of excitation were most prominent in the homolateral parasagittal plane (0.5 mm. from midline). When the nerves from the inferior rectus and inferior oblique muscles were stimulated, the centers of excitation were prominent in the midsagittal plane.

In the contour maps, there was a considerable overlap in the regions excited by the various individual nerve stimulations, though the centers of maximum excitation had individual localizations. In different experiments, the contour maps of a given muscle had only slightly different configurations and the centers of maximum excitation were fairly constant (Fig. 7).

3. Individual extraocular muscle representation. Evoked potentials, probably due to excitation of somas and dendrites, were
Fig. 5. Contour maps of the electrical fields recorded after electrical stimulation of the individual muscle branches of the oculomotor nerve in the cat. The lines represent 50 μv steps from outside to inside. It was not possible to draw contour lines to indicate over 350 μv in several diagrams. The maximum potentials (measured to the nearest 10 μv) obtained are indicated under each diagram. When there is more than one center of excitation in a diagram, the center with maximum potential is indicated. All contour maps represent negative electric fields except those labelled +, which are positive. In the medial rectus at 0.5 msec after stimulation the electrical changes were positive but less than 50 μv, and, therefore, they were not illustrated.

Responses from stimulating the nerve to the inferior oblique were mainly seen in the homolateral caudal part of the region (A0.5 to 2). Responses from the medial rectus nerve were mainly in the homolateral central part of the region (A1 to 3) and from the inferior rectus in the homolateral rostral part (A2 to 4), although some responses were seen throughout the region. Responses to the superior rectus nerve were mainly observed in the contralateral caudal part of the region, but there were responses also seen in the homolateral caudal part.

4. Retrograde degeneration studies. The superior rectus muscle and nerve were extirpated in 3 cats and retrograde degeneration studies were performed on the midbrain parenchyma. Large motoneurons

recorded in the midbrain from a region about 1 mm. from either side of the midsagittal plane and extending about 5 mm. in a rostral-caudal direction (Fig. 8, m to l, A0.5 to 5).

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Fig. 7. The contour maps from three different experiments involving inferior oblique nerve stimulation are superimposed. The left diagram represents the midsagittal plane and the right a parasagittal plane 0.5 mm. away from it. The evoked potentials were recorded 1.0 msec. after the stimulus shock.

Fig. 6. Contour maps at 1.0 msec. after superior rectus nerve stimulation in three parallel sagittal planes, 0.5 mm. apart. A sharply localized excitation is seen in the contralateral caudal part of the nucleus (c).

Fig. 8. Schematic representation of the individual extraocular muscles in the nucleus, in: midline; clear circles, amplitude of action potentials 100 to 199 μV; black circles, 200 to 299 μV; dotted circles, 300 μV or higher.

were observed to be undergoing degeneration on both sides of the midline (Fig. 9).

Discussion

Antidromic stimulation techniques have been employed to study the physiological characteristics of motoneurons of the spinal cord, to investigate synaptic transmission within the oculomotor nucleus, and to correlate the morphology of the oculomotor nucleus with the configuration of the evoked action potentials.1,2 Shimo-oku3,7 and others4-6,11 have previously recorded, after stimulation, the triphasic potential configurations shown in these experiments (Fig. 1).

The oculomotor nerve is believed to be composed of both efferent and afferent fibers.12 Communications between the oculomotor and trigeminal nerves in the orbit have been reported in the cat.13 Afferent pathways in the oculomotor nerve have been traced to cells in the oculo-
motor nucleus\textsuperscript{16, 17} or close to it, and to cells in the posterior commissure.\textsuperscript{17-19}

In the present experiments, the evoked potentials could have arisen antidromically from the efferent fibers or orthodromically from the afferent fibers in the oculomotor nerve. The typical triphasic potential with a short latency (0.3 to 0.4 msec.) was evoked, as well as more complex potential configurations (Figs. 2 and 4).

It is suggested that the triphasic potentials represent excitation within the oculomotor nucleus for this following reason: The distance between the stimulating and recording electrode was approximately 4 cm. In the experiments it required from 0.3 to 0.4 msec. for the impulses to travel along the oculomotor nerve from the stimulating to the recording electrode. If multiple synaptic pathways were interposed between the stimulating and recording electrodes, the latency of the response would be longer than 0.4 msec. because of synaptic delay.

The second wave of the complex potentials probably represents incidental excitation of internuncial neurons in the nucleus. Since these potentials were found only in small localized areas, it was not possible to draw contour maps.

The oculomotor nucleus in the cat has been described as being about 2 to 3.2 mm. long, 2 to 2.4 mm. high, and 0.9 to 1 mm. wide.\textsuperscript{20-22} The rostral end is believed located just posterior to the termination of the third ventricle and the caudal end at the junction of the superior and inferior

Table I. Decussation of the neurons of the oculomotor nucleus

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Crossed fibers</th>
<th>Region of crossing in the nucleus</th>
<th>Muscle with crossed fiber</th>
<th>Representation of individual muscles, rostral to caudal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spitzka\textsuperscript{25}</td>
<td>+</td>
<td>Caudal</td>
<td>Medial rectus</td>
<td>IR-MR-IO-SR</td>
</tr>
<tr>
<td>Bach\textsuperscript{26}</td>
<td>+</td>
<td>Middle and caudal</td>
<td>Inferior rectus (middle), superior rectus (caudal)</td>
<td>IR (lateral)*</td>
</tr>
<tr>
<td>Panegrossi\textsuperscript{20}</td>
<td>+</td>
<td>Caudal</td>
<td>?</td>
<td>IR-IO-MR-SR</td>
</tr>
<tr>
<td>Benjamin\textsuperscript{22}</td>
<td>+</td>
<td>Caudal third</td>
<td>?</td>
<td>SR (mainly contralateral)</td>
</tr>
<tr>
<td>Szentágothai\textsuperscript{24}</td>
<td>+</td>
<td>Caudal</td>
<td>Superior rectus and levator</td>
<td>IR-MR-SR</td>
</tr>
<tr>
<td>Danis\textsuperscript{23}</td>
<td>?</td>
<td>--</td>
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<td>--</td>
</tr>
<tr>
<td>Shimo-oku and Jampel</td>
<td>+</td>
<td>Caudal</td>
<td>Superior rectus (levator not studied)</td>
<td>IR-MR-IO-SR</td>
</tr>
</tbody>
</table>

\textsuperscript{*IR, inferior rectus; MR, medial rectus; IO, inferior oblique; SR, superior rectus.}

Fig. 9. Photomicrograph of degenerating motorneurons of the superior rectus nucleus of the cat. The superior rectus was extirpated and the cat was killed 10 or 15 days later. Note the bilateral cell degeneration. (Thionin stain. Original magnification x250.)
In our experiments evoked potentials were recorded from an area beneath the superior colliculus that was 5 mm. long and 1 mm. to either side of the midline. This region is probably larger than the oculomotor nucleus, since it represents the extent of the electrical fields.

In our experiments evoked potentials elicited from individual nerve branches predominated in different areas within the region of the oculomotor nucleus, although it appeared that individual cells supplying each muscle were scattered throughout the nucleus. The superior rectus muscle was the only extraocular muscle which was represented on both sides of the nucleus (Table 1). From these observations, a schema of the oculomotor nucleus of the cat was devised (Fig. 8). This schema agrees, for the most part, with the work of Bach and Danis, but disagrees with Szentagothai in regard to the representation of the inferior oblique muscle (Table 1).

REFERENCES