Parameters of Phosphene-Inducing Electric Stimulation of the Cat Visual Cortex via Implanted Surface and Intracortical Electrodes

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Translated from *Byulleten' Eksperimental'noi Biologii i Meditsiny*, Vol. 145, No. 1, pp. 8-11, January, 2008
Original article submitted May 14, 2007

Parameters of phosphene-evoking electrical stimulation of cat striatal cortex via electrodes of different types (surface and intracortical) were studied. Similar actions (paw raising) in response to the light pattern and to phosphene-inducing electric stimulation of the striatal cortex were demonstrated. It seems that the animals associated phosphene sensations with light patterns.

Key Words: *vision prosthesis; phosphenes; electric stimulation of striatal cortex; cat; electrodes*

Due to the progress in microelectronics and accumulation of data on structural and functional organization of the cerebral visual analyzer, creation of artificial systems for human vision rehabilitation gained a real basis. The most important problem is creation of an interface between the brain and technological component of the visual prosthesis for retinal and cortical systems [2-4]. Electrodes as a part of the implant should be biologically compatible and fit for long functioning in aggressive medium of the brain, which necessitates the use of in-depth electrodes causing minimum damage to the brain.

We compared the parameters of electrical stimulation with electrodes of different types implanted into cat striatal cortex and inducing phosphene sensations.

MATERIALS AND METHODS

Solitary in-depth electrodes (nichrome, 0.2-0.3 mm in diameter, n=7-8) were implanted in layers 3-4 and 5-6 of field 17 of the visual cortex of one hemisphere and surface electrodes (epidurally, gilt, 1 mm in diameter, n=7-8) were implanted in field 17 of the other hemisphere. The coordinates of electrode implantation were planned on the skull according to the Atlas [5]. A total of 63 electrodes were implanted (3 cats); of these 4 in-depth and 2 surface electrodes proved to be faulty.

Other animals were implanted 16-channel (4×4) electrode matrices with integrated stimulation system (NeuroCortex). The diameter of each matrix electrode together with platinum coating was 50 μ, length 2.5-3.0 mm, distance between each row and column about 500 μ. A fragment of the skull bone (10×15 mm^2) above field 17 was cut out, the dura mater was cut and moved aside, and the matrix was carefully (to prevent damage to blood vessels) pressed to the brain perpendicularly to the hemisphere surface. After the initial shape of the brain surface slightly depressed under the electrodes was restored, the compressing device was removed, the electrode contacts with the brain were tested, and the skull bone was placed back and sealed with acryloxide. A plug-and-socket unit with a thin cable was fixed with screws close to the frontal part of the bone under which the supraorbital cavity of the skull was located. A similar matrix with surface electrodes was implanted in the striatal cortex of the other hemisphere.

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0007-4888/08/1451-0004

Several days after implantation of electrodes, conditioned food reflex was trained in the cats. In order to limit animal movements, they were dressed in vests fixed to bars with ropes. A visual pattern presented by 4-7 light beams of about 1 degree of arc (phosphene field simulation). The animal was trained to raise a paw in response to the light pattern; a piece of meat served as the reward. After attaining 70-100% conditioning after 5-8 days of training, the latency of the reflex initially varying from 2 to 10 sec, stabilized at the level of 3-5 sec, this indicating reflex stability. At the next stage of the study, animal eyes were covered with thick cloth and electrical stimulation of the cortex was delivered from the electric stimulator (Nihon Kohden) through one or several electrodes simultaneously. The stimulation parameters (strength of current, pulse polarity and length, frequency and duration, and duty factor) were modified at a preset configuration of electrodes until the animal started to raise the paw (Fig. 1). The reflex latency in response to the first stimulation sessions was longer with the eyes closed. It seemed to be caused by "attribution" of the phosphene sensations to the light patterns. After the threshold electric stimulation was attained, the latent period of the reflex was recorded during subsequent stimulation, similarly as with the eyes open.

Paw raising in response to cortical stimulation was not caused by stimulation of the nerve pathway from the cortex to motor centers, *e.g.* to the superior colliculi associated with such reflex reactions as whiskers twitching, head turns, eye and limb movements, and others. This movement was similar to reflex reaction to light: the animal sometimes raised the other (nondominant) paw.

Impedance of each electrode was regularly measured after several experiments throughout the entire study (Fig. 2). Stimulation current was evaluated for different numbers of stimulating electrodes and their impedance (Fig. 3). Each animal was used in experiment over 8-10 months. The values of electrode impedance and threshold stimulation currents changed during this period, sometimes to the degree when phosphenes disappeared.

RESULTS

The study was carried out on cats, because their visual system, despite certain important differences (for example, the geniculo-extrastriatal projections to the cortex and the presence of "second visual system" not detected in humans), is close to human visual system by its structural and functional organization. In addition, due to high "intellectual level" of cats, it is possible to detect phosphenes in behavioral reflexes in response to electrical stimulation of the striatal cortex.

Similarity of cat reflexes in response to stimulation with different electrodes suggests similar sensations during stimulation via surface and intracortical electrodes. Polarity and shape of stimulation pulses (+, -, +/- or -/+) cause virtually no appreciable changes in sensations, but bipolar sti-

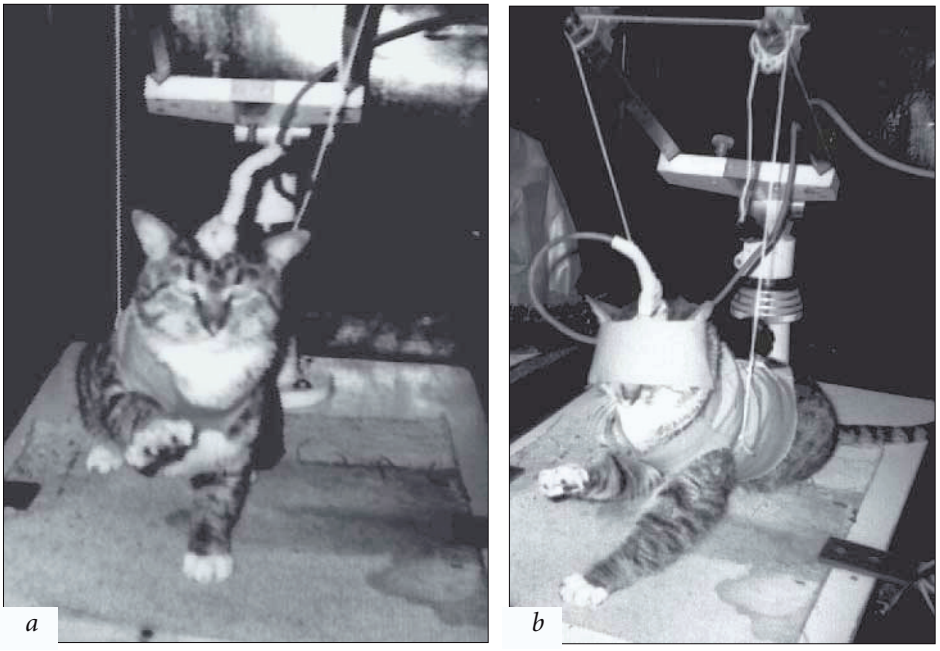

Fig. 1. Conditioned reflex of cat to light pattern (*a*) and electric stimulation via several electrodes implanted in field 17 (*b*).

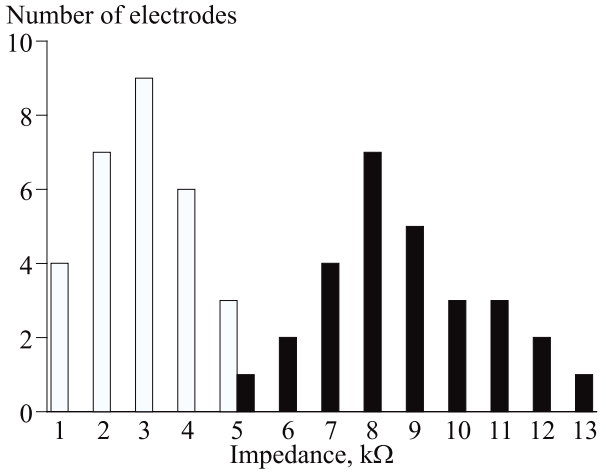

Fig. 2. Histogram of impedance distribution for surface (light bars) and in-depth (dark bars) electrodes.

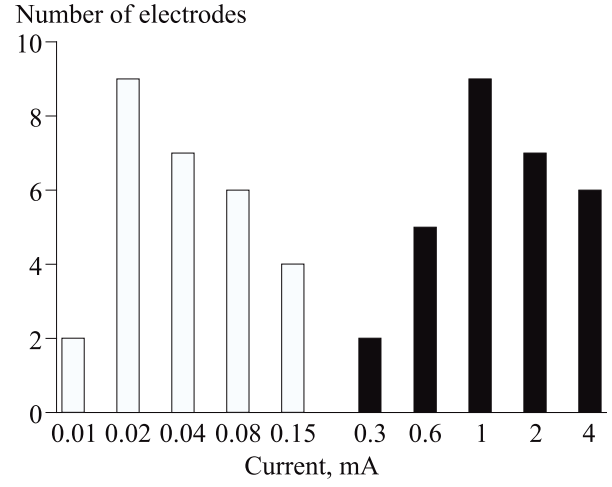

Fig. 3. Histograms of distribution of surface (light bars) and in-depth (dark bars) electrodes by stimulation thresholds.

mulation is preferable for reducing brain destruction. The duration of stimulation pulses via in-depth electrodes was 0.1-0.5 msec and via surface electrodes 0.3-1.0 msec. Phosphenes better emerged in response to cathode-anode pulses during microstimulation of the deep layers of human striatal cortex [6]. Stimulation frequency of 25-100 Hz was used for all electrodes, duration 1-2 sec for in-depth and 1-3 sec for surface electrodes. Such stimulation parameters as pulse length, frequency, duration, and polarity have certain limits and are applied irrespective of the stimulated cortical area, in contrast to the stimulation current. In order to evoke visual sensations, including phosphenes, any pulsation from the lateral geniculate body or direct electrical stimulation of the cortex should reach layers 3-4 of the striatal cortex, in which the bodies of the main cortical neurons (pyramidal, intercalar, *etc.*) are located. During surface stimulation, it propagated from the stimulated area of the cortex by several pathways: via neurons of layer 1 (dendrites, axons) lying parallel to the cortical surface and connecting large areas of cortical surface and via the corpus callosum fiber system. These pathways shunt the currents which are to induce phosphenes. Strong currents are needed for creating pulses which will reach the intermediate and associative cortical neurons and induce sensations. Such currents are used in the first cortical prostheses [2,3]. By the parameters of surface electrode stimulation (Fig. 3) our results largely coincide with these data. Stimulation was more adequate and approximated the actual situation when intracortical electrodes were used: the pulsation was similar to that propagating via afferent pathways from the lateral geniculate body, and hence, the currents are by 1-2 orders of magnitude lower than in surface stimulation (Fig. 3). It is noteworthy that stimulation of the same layers with microelectrodes results in phosphene induction in humans and monkeys by even lesser currents (~2 μA) [6,7].

Behavioral reaction of cats to "realized" phosphene sensations is a more reliable criterion in comparison with saccadic reactions used by some authors, because in this case we cannot be completely sure that the reflex saccadic reaction of the animal is caused by phosphene generation in the brain, but not by stimulation of the structural pathways from the striatal cortex to the superior colliculi.

The results indicate that surface electrodes are easy to implant, but great stimulation currents are undesirable and dangerous for long use.

The use of intracortical electrodes is fraught with many difficulties in bloodless atraumatic implantation. Development of electrode technology should be directed towards the increase in the number of electrodes in parallel with reduction of their diameter and impedance. The material for electrodes should be biocompatible, so that brain tissue was not damaged.

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