Short communication

Visual sensations produced by optic nerve stimulation using an implanted self-sizing spiral cuff electrode

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Abstract

A blind volunteer with retinitis pigmentosa was chronically implanted with a self-sizing spiral cuff electrode around an optic nerve. Electrical stimuli applied to the nerve produced localized visual sensations that were broadly distributed throughout the visual field and could be varied by changing the stimulating conditions. These results demonstrate the potential for constructing a visual prosthesis, based on electrical stimulation of the optic nerve, for blind subjects who have intact retinal ganglion cells. © 1998 Elsevier Science B.V. All rights reserved.

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Following upon Brindley’s groundbreaking investigation on occipital cortex stimulation [2], several similar attempts to electrically evoke a visual sensation in blind individuals have been undertaken [6,13]. Recently, electrical stimulation of the peripheral visual system has also been suggested. In retinitis pigmentosa photoreceptor cells disappear, while ganglion cells and their axonal processes are spared [11,14]. Direct electrical activation of these cells using retinal implants is now investigated [7,12]. The work we report here consists in an alternative to retinal implant for vision rehabilitation in totally blind retinitis pigmentosa patients. Optic nerve electrical stimulation, with a multi-contact electrode and utilizing selective activation techniques [4,16], provides an opportunity to create phosphenes over a wide portion of the visual field with only a few contacts and a few stimulators.

Selected among six totally blind candidates with retinitis pigmentosa [3], a 59-year old female volunteer, who gave her informed consent, has been chronically implanted with a self sizing spiral cuff electrode [10,16] around her right optic nerve. This subject was affected by a dominant autosomal form of retinitis pigmentosa whose first symptoms appeared when she was 28. She was left with a mere light perception from the age of 40, and was diagnosed totally blind at 57. This project fully complies with the Declaration of Helsinki, and was approved by the local Ethics committee. The four-contact self-sizing spiral cuff electrode was designed by the authors, in collaboration with NeuroTech Louvain-la-Neuve, Belgium, and fabricated by Axon Engineering (Willoughby, OH 44094, USA). The electrode was intracranially implanted through a pterional transsylvian approach and installed around the optic nerve after careful dissection of the arachnoidal strands. Electrode leads were brought outside the skull, and through the skin where they ended in an external connector (Fig. 1).

Stimulation started on day 2 post-surgery. Then the volunteer progressively worked up to a level of two 3-h-stimulation sessions a week. Charge balanced single pulses and trains were used. Stimulation was either monopolar, using a surface indifferent anode, or bipolar between two contacts within the cuff. Charge density was always kept below 150 μC/(cm² phase) up to 50 Hz [below 50 μC/(cm² phase) up to 333 Hz], corresponding to a charge per phase of 300 nC/phase (respectively 100 nC/phase)
Fig. 1. Sketch of the implanted material. The self-sizing spiral cuff electrode was implanted intracranially and the first part of its cable lay on the dura mater up to the inferior part of the skull opening. After crossing the dura on the lateral aspect of the skull the lead passes through the skull. The second part of the cable courses below the skin and along the outer surface of the skull. A subcutaneous connector is embedded in the skull, over the ear. A second lead, with an open helix, passes down the neck to exit the skin below the clavicle (see the small lozenge), and is terminated with an external connector. The purpose of the implanted connector is to allow removal of the easily accessible implanted material if needed, or to provide a means of self-sizing cuff electrode to be subsequently connected to an implanted stimulator.

with a contact area of 0.2 mm². Determination of current intensity thresholds for generation of a phosphene was done using the two-staircase limit method [5].

To assess phosphene location, a pointing hemisphere with a radius of 0.45 m was used. The volunteer’s head was stabilized in front of the hemispheric surface using a frame to support her forehead, chin and parietal skull. Her right eye was positioned at hemisphere center. The right EOG was recorded, and eye movements were monitored with a TV camera. When ready for a stimulus, the volunteer places her head in fixed position, constrained by the frame, and reaches into the hemisphere to place her left index finger on the fixation point (a polymer disk at the intersection of the visual axis [1] with the hemisphere). She was then instructed to ‘look at’ the fixation point with a steady gaze throughout the stimulation test run. The test run was delimited by two beep sounds. With her left forefinger still in contact with the fixation point, as a proprioceptive reference, the subject then indicated the evoked phosphene, with the right hand fingers, as a shape on the hemisphere. Phosphene characteristics were recorded, which included position, dimensions and organization, subjective brightness, dots diameter, foreground and background colors, motion, etc. Occasionally, some sham stimulations (no stimulation pulse between two beep sounds) were delivered. They systematically resulted in a lack of perception by the subject.

At day 118 post-surgery, some 1465 phosphenes had been documented. Transverse thresholds reached generally twice or more the corresponding monopolar thresholds. This did indirectly confirm the proper electrode position. We have not observed a threshold increase over the time since implantation. Electrical stimuli applied to the contacts in the self-sizing spiral cuff electrode have never evoked sensations other than visual. Most phosphenes were reported to consist of a set of dots either in a cluster of 2 to 5, or arranged in rows, arrays, or lumps of 6 to 30. Dot diameter ranged from 8 to 42 min of arc (1 to 5.5 mm at the distance of 0.45 m). Sometimes, a kind of surround of lesser brightness was described around each dot in a phosphene. Solid lines, bars, or triangles devoid of dot structure were occasionally reported, usually near percep-
tion threshold. Phosphenes were often reported as colored. In the first days after surgery, they generally appeared to our subject as gold-yellow against a black visual field. Thereafter blue, white, or plain yellow colors were described. With dot phosphenes, the otherwise black visual field sometimes appeared colored in blue, red, or yellow, in between the dots. Occasionally, a solid colored surface (red, or yellow) was described adjacent to the envelope of a dot phosphene.

Among 156 phosphenes collected at the hospital up to day 8 post-surgery, 37% were described as moving; most often, they consisted of lines, instead of dots. Afterwards, 1308 of the next 1309 phosphenes appeared consistently immobile and steady.

Current intensity thresholds for phosphene perception were determined using five pulse duration (25, 50, 100, 200, and 400 μs). This study included single pulses, as well as trains of 5, 9, and 17 pulses, respectively, generated at 40, 80, and 160 Hz. As in the classical strength–duration curve [8] current intensity thresholds diminished with increasing pulse duration. Furthermore, as illustrated in Fig. 2 threshold clearly diminished when train frequency increased, and might even be as low as 30 μA for pulses of 400 μs in duration.

An additional observation resulting from this strength–duration–frequency representation was that, for a given

![Graph](image-url)
Contact in the cuff electrode, attributes (brightness, color, size, organization, position, etc.) of a phosphene, perceived at threshold for a specific pulse duration and train frequency, usually differed from those documented at threshold for another pulse duration and/or train frequencies. Furthermore, phosphene attributes reported by our subject differed when the same contact was stimulated at the same values of pulse duration and current but at different frequencies.

The attributes of the phosphenes were usually consistent for trials repeated over a short period of time. As an example when, for a first phosphene, standard deviations of center of gravity position as a function of time are $1.1^\circ$ horizontal and $0.6^\circ$ vertical (seven measurements made on day 84 for 93 min), for a second phosphene, they reach $2.6^\circ$ horizontal and $3.2^\circ$ vertical (nine measurements made on day 81 for 182 min, and eight measures made on day 84 for 101 min).

Fig. 3. Example of the retinotopic arrangement of phosphenes according to the activated contact in the self-sizing spiral cuff electrode. When a given stimulating condition was applied to a given contact within the cuff electrode, a phosphene was reported by the volunteer provided stimulation threshold had been reached. By convention, phosphenes elicited by the activation of a same contact are represented in the figure as colored with the same hue. Contact position within the circular cuff is expressed in degrees. The contact–quadrant relationship which resulted from the optic nerve electrical activation is consistent with the orderly arrangement of both quadrants and contacts. This sample of 64 phosphenes collected near threshold also illustrates the broad distribution of relatively small phosphenes within the volunteer’s visual field. All the illustrated phosphenes were perceived as motionless.
Fig. 4. Retinotopic organization of the volunteer's optic nerve. The probable position of the 4 contacts (labeled 0°, 90°, 180°, and 270°) around the optic nerve is indicated on the right; on the left, the quadrant–contact relationship refers to the position in the visual field of phosphenes elicited when stimulating through a given contact (see also Fig. 3). Compared to clinical data related to the retinotopy of the human optic nerve [9], when a slant of about 60° of the vertical meridian optic nerve projection, relative to the vertical axis, is reported, we observed a more limited inclination of some 20°.

Phosphenes were reported to have been perceived over a large portion of the visual field, up to 35° upwards and 50° downwards on the vertical meridian and 30° leftwards and 30° rightwards on the horizontal meridian. Near threshold, we found a good retinotopic correspondence between the contact position used for a given stimulation within the cuff electrode, and the quadrant of the visual field in which the volunteer drew the related phosphenes. Fig. 3 illustrates this relationship for a sample of 64 phosphenes with a broad distribution within the visual field.

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As expected, phosphenes location depended on gaze direction [15]. A steady gaze oriented sideways with respect to the fixation point during the stimulus, or a saccade ending just before the stimulus, resulted in a phosphenes location consistently referring to gaze orientation at the time of the electrical stimulation. Similarly, any gaze displacement, either after a while, or immediately after the stimulus, resulted in a phosphenes location steadily referring again to gaze orientation at the time of the stimulation, in this case, before the movement. Stimulation thus resulted in phosphenes coded in spatial co-ordinates, i.e., the algebraic subtraction of actual gaze co-ordinates, from retinal co-ordinates frozen at stimulation time. Therefore, in order to secure an accurate measurement of phosphenes attributes, care was taken to explain to our subject the importance of maintaining a fixed gaze during the presentation of each test stimulation.

In summary, the axons of retinal ganglion cells in this retinitis pigmentosa blind volunteer have thus been successfully activated by electrical stimuli applied to the optic nerve to evoke many distinct phosphenes over a large portion of the visual field. Slight changes in the attributes of the phosphenes seem to occur over time, which suggest that some form of learning or remodeling may occur. The overall picture that emerges from these preliminary studies is one of a dormant sensory system that can be reactivated and potentially used for functional purposes.

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