Visual Perception Elicited by Electrical Stimulation of Retina in Blind Humans

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**Objective:** To evaluate the feasibility of bypassing damaged photoreceptors and electrically stimulating the remaining viable retinal layers to provide limited visual input to patients who are blind because of severe photoreceptor degeneration.

**Methods:** In the operating room with the patient under local anesthesia, focal electrical stimulation of the retinal surface with brief biphasic pulses was performed using small probes inserted through the sclera. The procedure was performed in five subjects who had little or no light perception. Three subjects had retinitis pigmentosa, one had age-related macular degeneration, and one had unspecified retinal degeneration from birth.

**Results:** Stimulation elicited visual perception of a spot of light (phosphenes). Subjects who previously had useful vision accurately localized the phosphenes according to the retinal area stimulated. Two subjects could track the movement of the stimulating electrode by reporting movement of the elicited phosphenes, and could perceive two simultaneous phosphenes on independent stimulation with two electrodes. In a resolution test, one of the subjects with no light perception in his left eye resolved phosphenes at 1.75° center-to-center distance (ie, 4/200 OS visual acuity).

**Conclusions:** Local electrical stimulation of the retinal surface in patients blind from outer retinal disease results in focal light perception that seems to arise from the stimulated area. Such findings in an acute experiment warrant further research into the possibility of prolonged retinal stimulation, improved resolution, and ultimately, an intraocular visual prosthesis.


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In retinal dystrophies such as retinitis pigmentosa (RP) and age-related macular degeneration, the photoreceptors (rods, cones, or both) and their supporting retinal pigment epithelium cells are damaged. In RP, with an incidence of at least one in 4000, typically a 10° radius, ie, legal blindness in the United States, is reached after 25 years. In many patients with RP who are older than 60 years, only rudimentary foveal vision remains, with gross movement or bright light visible straight ahead, and no appreciable vision in the periphery. Eventually, even light perception may disappear. Age-related macular degeneration is the leading cause of vision loss among adults aged 65 years and older in Western countries. No treatment stops, much less reverses, the loss of photoreceptors in RP or age-related macular degeneration.

The traditional approach to vision rehabilitation in these patients has been to use the remaining vision with the help of magnifiers, telescopes, and other optical aids. If no useful vision can be obtained this way, auditory or tactile information is substituted for visual input (eg, braille, cane travel, and electrotactile and vibrotactile devices). Attempts have been made to remedy or alleviate the loss of vision by replacing damaged cells or by electrically stimulating an undamaged proximal level, bypassing damaged cells. Replacement of damaged photoreceptors has been studied in animals through transplantation. Although there are indications that transplanted photoreceptors can make functional connections, many questions remain about the optimal methods to achieve long-term graft survival and functionality in a human eye.

Electrical stimulation at a proximal level (ie, the primary visual cortex) has been attempted and has the advantage of...
SUBJECTS AND METHODS

Subjects were tested from January 1, 1991, to December 31, 1992, at the Duke Eye Center at Duke Medical Center, Durham, NC, and from January 1, 1992, to December 31, 1994, at the Wilmer Eye Institute at The Johns Hopkins University, Baltimore, Md. Five subjects were selected whose best vision was light perception in one or both eyes.

All experiments were performed in the subject’s worse-seeing eye. Two experiments (one each in subjects 1 and 2) were performed at the Duke Eye Center and six experiments (one in subject 1, two in subjects 3 and 4, and one in subject 5) at the Wilmer Eye Institute. The subjects and their families were fully informed of the experimental procedure, and they signed consent forms approved by institutional review boards at both institutions. The consent form emphasized that no practical benefits could be expected from the procedure, and that a prosthetic device, if feasible, would take many years to develop. All subjects indicated that they were happy to participate if there was any chance that these experiments would lead to methods that might help blind patients, even beyond the study group’s lifetime.

Subjects 1, 3, and 4 had late-stage RP; subject 2 had early-onset retinal dysfunction of unknown cause and had never had form or color vision. Subject 5 had lost vision in each eye from a massive subretinal hemorrhage that was a complication of macular degeneration, a rare condition.

Before the intraocular procedure, electrical pulses were generated by the same current source used for retinal stimulation and supplied with a contact lens electrode to the eye that was to be stimulated. This was done to confirm that the subject perceived light when the eye was stimulated globally, ruling out complete loss of the retinal ganglion cells and their axonal fibers.

Three types of stimulating probe were used in the intraocular tests. Each contained one or more electrodes formed by a pair of metal conductors (poles), so stimulus currents could be applied between the two poles of an electrode (bipolar), or between one of the poles and a distant reference electrode (monopolar); in this case, the second pole was insulated from the current source. In experiment 5, when more than one electrode was used for stimulation, current was applied to both electrodes simultaneously using isolated current sources. In experiment 7, multielectrode stimulation was done in rapid succession using a demultiplexer to prevent electrical interactions between electrodes.

The first probe, shown in Figure 1, consists of two Teflon-coated platinum wires. The exposed tips of these wires have been molded into hemispheres 200 µm in diameter, with a center-to-center separation of 300 µm. The wires are embedded in silicone and housed in a retractable stainless steel sleeve. This sleeve is insulated from the wires and retracted 7 mm into the vitreous cavity during stimulation, so as not to influence the electric field. To get information about the obtainable resolution, in later experiments a second probe identical to the first was introduced through a second opening in the sclera, and the two probes were placed over the retinal surface in close proximity.

To allow multiple stimuli at separations below 1 mm, and to allow more accurate measurement of the separation between the probes, which was necessary to study spatial resolution of the phosphenes, probe type 2 was developed. This probe with multiple electrodes is shown in Figure 2. It was built in collaboration with PI Medical (Portland, Ore) and contains three electrodes formed by three transversely cut coaxial conductors (center conductor diameters 50, 100, and 100 µm; center-to-shield dielectric thickness 60, 90, and 110 µm; shield thicknesses about 50, 50, and 80 µm), and an optical fiber, all encased in a 17½-gauge stainless steel cannula that was insulated from the conductors. The exposed metal surfaces of the coaxial conductors have been gold-plated. This probe was used in the seventh experiment.

Probe 3 was developed for experiment 8, in which we explored the influence of probe geometry in conveying shape information. This probe, shown in Figure 3, consists of two platinum (90%) and iridium (10%) wires, embedded in silicone in a 17½-gauge cannula. At the tip of the cannula, the wires have been bent to run in parallel across a homopolymeracetal (Delrin, Dupont, Wilmington, Del) surface; the length of these exposed wires is 850 µm. Each wire is 125 µm in diameter. Four versions of this probe were used, with the tip surface perpendicular or slanted at 60°, and center-to-center separations 250 µm or 375 µm.

Stimulus delivery was controlled by computer hardware and software. In the first six experiments, 286 microprocessor (2402! Tekmate, Tektronix, Beaverton, Ore) coupled with an analyzer (2630 personal Fourier analyzer, Tektronix) was used to generate the waveforms, and a custom-designed optically isolated constant-current generator controlled the injected current. In the last two experiments, a computer system (Centris 650, Apple Macintosh, Cupertino, Calif) with LabView 3.0.1 software (National Instruments Inc, Austin, Tex) was used for waveforms.

Continued on next page.
form generation, followed by a custom-built optically isolated constant current generator and a custom-built 1:16 demultiplexer. All stimuli were biphasic, charge balanced; if the configuration was monopolar, the stimulus polarity was usually cathodic-first. Typically, a delay equal to the phase duration was inserted between the two phases as shown in Figure 4. The stimulus selection was based on efforts to minimize the threshold charge density at the stimulating electrode surface. Charge density limits are important to avoid irreversible toxic reactions that can occur at the electrode-tissue interface.23 These limits are calculated by dividing the charge (ie, current integrated during a single phase) by the surface area of the smaller of the two electrode poles.24 These limits are established for long-term electrical stimulation of neural tissue and depend on electrode material and stimulus waveform.

Using a three-portal pars plana vitrectomy surgical procedure, with the patient under local subconjunctival anesthesia, the probe and an optical fiber were placed into the subject’s vitreous cavity. The anesthetic would last for 45 to 60 minutes, which (after 15 minutes of surgical preparation) leaves 30 to 45 minutes for the stimulation procedure. The surgical procedure, including the conversation between subject and experimenters, was videotaped using a camera and microphone built into the surgical microscope. The stimulating probe was placed closely over the retinal surface, without touching (we estimate the distance at 0.5 mm), and repeated electrical impulses were applied at a rate of 1 to 2 per second. Probes were positioned in the macular region (ie, inside the vascular arcades). One of four quadrants was stimulated. Each quadrant was coded with a number 1 to 4 as shown in Figure 5, allowing the experimenters to communicate which retinal area was being stimulated without informing the subject.

The experiments did not follow a rigorous psychophysical protocol. Although paradigms such as two-alternative forced choice would allow the most objective evaluation of the results obtained, the setting of these experiments does not lend itself to such rigor. The subjects are not trained psychophysical observers, so they may find it difficult to localize a percept more precisely than by quadrant, or estimate its size by comparing it with a known object held at a known distance. Moreover, the subjects were in the unfamiliar setting of an operating room. In the limited time available, the experimenters had to find timing and amplitude settings in which subjects could see a percept, bring the stimulus to a level where they could reliably see it, and use the remaining time to elicit as much information as possible about percept appearance, parameter (location, strength, duration, rate), dependence. Finally, subjects were not briefed in detail about the type of percept they were likely to experience, for several reasons. First, we believed that it was important to lead the subject as little as possible. Second, it was not certain a priori that all subjects would have similar percepts. Finally, all subjects mentioned that, in retrospect, it would have been difficult to describe the visual percepts to them beforehand.

Throughout the experiments, controlled electrical pulses were applied between the two tips of an electrode (bipolar), or between one of the tips and a distant reference electrode attached to the subject’s ipsilateral shoulder (monopolar) with the other tip not connected; a standard electroencephalographic electrode was used as the return electrode in the monopolar case. Stimuli were usually applied with 0.5- to 2-second intervals, in trains of 5 to 10. They were initially short and weak (0.1 microseconds, 100 µA), and then increased in strength and duration until the subject reported seeing a repetitive visual phenomenon (typically, 1 to 4 microseconds, 300 to 800 µA). The stimulating current was increased in steps of 20% until the subject could reproducibly verify each stimulus pulse by counting out loud the occurrence of phosphenes. Only if this was well established did we proceed. The lowest stimulus charge density at which the subject could perceive every delivered pulse was defined as threshold charge. By interspersing subthreshold stimuli, we verified that no positive responses were given; in all experiments, we found these to be rare or nonexistent.

During the remainder of the experiment, subjects were asked to describe (1) the perceived location of the visual phenomenon, to verify that this location corresponded to the retinal area directly beneath the probe; (2) the visual experience, to study the dependence of perceived size and brightness on stimulus location and strength (ie, duration and amplitude); (3) changes as the repetition rate of stimulation was varied, to determine possible changes of the visual percept at different stimulation rates; at higher stimulus rates, this provided a crude measure of temporal resolution (“flicker fusion”); and (4) if multiple sites were stimulated, the percept, to determine if multiple phosphenes could be resolved. All descriptions were left to the subject, without learning before the experiment or prompting as stimuli were being presented. Only if the subject had trouble describing an aspect of the percept (eg, size), was a choice given by providing multiple suggestions.

No complications of the surgery, such as endophthalmitis or phthisis, were encountered.

electrodes) subtending a visual angle of 1.7°, or a 0.5-mm area of the central retina, would allow good visual acuity (20/26) with a constricted visual field.17 Similarly, a coarser 25×25 array would enable mobility in environments not requiring a high degree of pattern recognition.18

To electrically stimulate retinas with photoreceptor degeneration, we electrically stimulated the remaining inner retina focialy and recorded the elicited responses from proximal ganglion cell axons, optic nerve fibers, and the visual cortex in animal models of outer retinal degenerations.1920 Our findings support the idea that the inner retina might be a location for useful electrical stimulation, provided nerve cells in the inner retina have not been affected by the disease process.

Because a retinal prosthesis as envisioned here would require, at a minimum, survival of ganglion cells, transsynaptic degeneration of the retinal neural elements must be studied carefully. In our experiments, which lasted 6 months, transsynaptic degeneration of the inner retina was minimal as evidenced by electrophysiologic and histologic findings.19 Moreover, inner retinal cells survive in rats that have an inherited photoreceptor degeneration.21 Similar results have been found in patients with RP by postmortem retinal histologic study.2223 Ganglion cells of the macular region in these preparations
RESULTS

Table 1 and Table 2 give the subjects’ vision status, the threshold charge densities at the stimulating electrode surface needed to elicit a visual experience, and the appearance of the stimulus. Phosphenes were elicited in all five subjects. The phosphenes were always described as brief, and they correlated exactly with the timing of electrical stimulation, confirming that no confusion with ambient light in the operating room occurred in subjects with light perception. The initial report usually required charge levels well above those later determined to be threshold. When the subject reported seeing phosphenes, the charge could be lowered by a factor of 2 to 3 before threshold was reached. In all cases, the size and brightness of the phosphenes were reported to increase slowly with increasing amplitude and duration of the stimulus pulse. The first experiment in subject 3 failed to yield any visual phenomena, but this was because a wire in the stimulating probe was broken. When the experiment was repeated several months later, this subject was able to describe the visual experience.

In all but the second subject, localization of the stimuli in areas 1 to 4 was found (Figure 4). Localization in subjects 4 and 5 was always in the retinotopically correct quadrant, but not as precise as in subjects 1 and 3, whose resolution was well within a 30° sector tangentially and estimated at under 10° radially (“Where do you see it?” “Nine o’clock, way out, moving down to 8 o’clock”, as quoted from the videotape of the third experiment). Subjects 1 and 3 described seeing movement when the probe was displaced across the retina during stimulation, and they correctly reported the perceived direction. Throughout the macular region, we found no apparent effect of stimulus location on perceived size and brightness of the phosphenes.

All but the second subject could give detailed descriptions of the visual phenomena, although once again subjects 1 and 3 were most precise in their descriptions (“What does it look like?” “Like a ring; like a black-eyed Susan”, [subject 3]). The second subject failed to describe location and appearance of the visual experience, but he said he saw light.

In the second experiment with subject 3 (experiment 5), we sought to obtain information about the achiev-
of a train of 10 and was repeated once. The subject reported seeing two doughnut-shaped objects, each about 6 mm (¼ in) in diameter and separated by a similar distance, if such objects were held at a distance of 30 cm (1 ft). The subject saw this percept with each pulse delivered during this period of testing. Stimuli were provided in monopolar and bipolar electrode configurations with otherwise the same stimulus parameters. Both configurations yielded the same visual percept. Similarly, we asked the subject to compare the percepts under anodic-first and cathodic-first monopolar stimulation, and the subject reported no difference.

During the same experiment, we increased the stimulus frequency until the subject saw the target as continuous. Because of the crudeness of stimulus timing under the software control used in this procedure, the highest frequency presented was 125 Hz, and the next highest 21 Hz; thus, we estimate that flicker fusion occurred between these two frequencies. With increasing stimulus rates, below and above flicker fusion, the subject reported an increase in brightness. To evaluate the effect of probe geometry on the elicited image configuration, in experiment 8, the third type of probe was used, with parallel elongated poles and a center-to-center distance of 375 μm. As with probe 2, we compared the percepts during monopolar and bipolar stimulation and found no difference. Initially the subject described this as “a pencil held at arm’s length.” Subsequently, in five separate runs consisting of a train of 10 pulses each, he always perceived a filled rectangular or elongated object 2.54 cm (1 in) long, and four times as long as wide, when viewed at a distance of 0.305 m (1 ft).

Focal electrical stimulation of the retinal surface elicited localized visual percepts in five subjects who were severely visually handicapped from end-stage photoreceptor degeneration. The three subjects with the characteristics of typical RP and the subject with the long-standing age-related macular degeneration described spatial and temporal aspects of the percept, including correct localization. Two subjects (1 and 3) volunteered reports of movement that accurately described repositioning of the probe. The subjects’ abilities to detect electrical stimulation at the inner retinal surface indicate that at least some of the retinal ganglion cells (and possibly other cell types) remain functional, in many instances more than a decade after loss of vision in the areas being stimulated.

Experiment 7 with three electrodes in a single probe (type 2) provided the most quantitative evidence that useful resolution can be achieved. The sizes reported by subject 1 (two 0.64-mm [¼-in] doughnuts separated by 0.64 cm [¼ in]) correspond with the dimensions of the probe. Electrode centers are separated by 435 μm, and the distance from the optical center of the eye to the retina is about 20 mm. Using the geometry of two triangles whose apices connect at the optical center, and assuming a viewing distance of 31 cm (12 in), a center-to-center target separation of 7 mm would be expected. Assuming 3.5/60 mm in the fovea, the center-to-center electrode separation of 435 μm

Table 1. Visual Acuity Histories of Five Male Subjects Who Participated in Retinal Stimulation Experiments

<table>
<thead>
<tr>
<th>Subject No./ Age, y</th>
<th>Diagnosis</th>
<th>Visual Acuity in Tested Eye</th>
<th>No. of Experiments Conducted on That Patient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/65</td>
<td>RP</td>
<td>LP</td>
<td>2</td>
</tr>
<tr>
<td>2/40</td>
<td>RD</td>
<td>LP (birth)</td>
<td>1</td>
</tr>
<tr>
<td>3/65</td>
<td>RP</td>
<td>No LP</td>
<td>2</td>
</tr>
<tr>
<td>4/60</td>
<td>RP</td>
<td>LP</td>
<td>2</td>
</tr>
<tr>
<td>5/94</td>
<td>AMD</td>
<td>No LP†</td>
<td>1</td>
</tr>
</tbody>
</table>

*RP indicates retinitis pigmentosa; LP, light perception; RD, retinal degeneration of unknown cause; AMD, age-related macular degeneration.
†Subject could perceive strong lights in periphery under dark-adapted conditions. All subjects were males.
Table 2. Subjects' Observations of Stimuli During Each Experiment*

<table>
<thead>
<tr>
<th>Experiment No./Subject No./Probe Type</th>
<th>Threshold, mC/cm²</th>
<th>Able to Localize</th>
<th>Size†</th>
<th>Shape</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1/1</td>
<td>0.40</td>
<td>Yes</td>
<td>Pea</td>
<td>Round</td>
<td>Yellow-green</td>
</tr>
<tr>
<td>2/2/1</td>
<td>0.95</td>
<td>No</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>3/3/1</td>
<td>0.16</td>
<td>Yes</td>
<td>Match head</td>
<td>Ring</td>
<td>Yellow</td>
</tr>
<tr>
<td>4/4/1</td>
<td>...</td>
<td>Yes</td>
<td>Pin</td>
<td>Round, lines</td>
<td>Yellow</td>
</tr>
<tr>
<td>5/3/1‡</td>
<td>0.28</td>
<td>Yes</td>
<td>Match head</td>
<td>Ring</td>
<td>Yellow</td>
</tr>
<tr>
<td>6/4/1</td>
<td>3.20</td>
<td>Yes</td>
<td>Pin</td>
<td>Round, lines</td>
<td>Yellow</td>
</tr>
<tr>
<td>7/1/2</td>
<td>13-70</td>
<td>Yes</td>
<td>Pea</td>
<td>Ring</td>
<td>Yellow</td>
</tr>
<tr>
<td>8/5/3</td>
<td>56</td>
<td>Yes</td>
<td>2.54 cm × 6 mm</td>
<td>Rectangle</td>
<td>White</td>
</tr>
</tbody>
</table>

*Ellipses indicate no data; question mark, inconclusive data.
†Sizes reported are a threshold stimulus for a target observed at a distance of 30 cm (1 ft).
‡During part of this experiment, a second probe of the same type was used.

corresponds to a resolution of 1.5° of visual angle. In the configuration described by the subject, the gap between the two dots was half this distance, i.e., 0.75°, or 45 arcminute. Based on the 1-arcminute gap in a 20/20 Landolt C, the subject's resolution thus was 20/900, or 4.4/200, i.e., crude ambulatory vision. Continued testing after further miniaturization of multiple electrodes is required to establish a true resolution limit.

Experiment 8 evaluated the effect of probe geometry on the shape of the generated visual percept. The estimate of a 4:1 aspect ratio for the filled rectangular or elongated visual percept is reasonable. The length of the wire is less than 1 mm; in the bipolar configuration, the field width should fall between 250 (the separation between the wires) and 500 μm (separation plus thickness); in the monopolar configuration, one can expect the field to be somewhat broader than the 125 μm wire thickness.

The small phosphene size and precise localization in our human data suggest that local elements near cell bodies of the neural elements of the inner retina are the primary targets of the electrical stimulus, rather than the passing axons of distant ganglion cells. A possible explanation for this phenomenon is that depolarization of a thin unmyelinated axon requires stronger electrical fields than that of a thicker element (e.g., the cell body). The precise course of events during electrical stimulation, and especially the site of stimulation, requires more detailed study.

The ability of our four subjects to localize the stimuli accurately bodes well for the application of retinal electrical stimulation for orientation and mobility. If accurate localization can be combined with increased resolution and external optical magnification, even the goal of limited reading in patients with no remaining useful vision may be achieved. Although a 32×32 array over a 0.5×0.5-mm area would yield 20/26 visual acuity, electrodes separated by as much as 90 μm would result in visual acuities in the range of 20/200, allowing reading with commonly used low-vision aids such as closed-circuit televisions or the Low Vision Enhancement System. The small discrepancy in these acuity measures may require clarification. The estimate of 20/26 visual acuity was obtained by Cha et al. using a 32×32-point square grid spanning 1.7° along the side, and a four-alternative forced-choice paradigm. The acuities reported here are based on a clinical rule of thumb equating 20/20 visual acuity to a 1-arcminute gap in a Landolt C, leading to a 20/32 visual acuity estimate for the layout of Cha et al. A 25×25 array with electrode spacing of 200 μm would yield a 30° visual field and 20/440 visual acuity, which would allow orientation and ambulation in a limited environment.

The threshold charge densities in our experiments ranged from 0.16 to 70 millicoulomb (mC)/cm², computed at the surface of the probe tips. Safe limits, preventing damage to electrode materials and surrounding tissue during chronic stimulation, are 1 mC/cm² using platinum electrodes, and 3.5 mC/cm² using activated iridium electrodes. More recent studies put the limits for activated iridium at 6 mC/cm². With improved design of stimulating probes for use closer to the retinal surface, and with optimized electrode configurations and stimulus waveforms, we expect to achieve effective stimulation below these limits.

Temporal frequency tests, although tentative because of equipment limitations, suggest that flicker fusion occurs at similar frequencies for electrically generated phosphenes and normal vision. The perceived increase in stimulus brightness with increasing repetition rate suggests that at least two parameters, stimulus strength and repetition rate, can be used to encode phosphene brightness in retinal electrical stimulation.

The failure of subject 2 to describe location and appearance of the visual percept can be attributed to damage to the inner retina or failure of the visual cortex to form proper percepts. Although we found no visible signs of inner retinal dysfunction, the latter assumption is plausible, because deprivation of form vision in early life leads to abnormal development of visual cortical circuitry.

Our findings show that it may be possible to restore some vision to affected portions of the retina in patients with RP and other photoreceptor degeneration, and that at least crude spatial resolution is feasible. We envision an implantable matrix of stimulating electrodes over the retinal surface. To encode a visual scene for brightness and contrast, the impulse charge, frequency, or both at each matrix element should be varied with the amount of light incident through the pupil onto the front surface of the matrix. Thus, the matrix should contain at least a photosensitive layer and a stimulation layer. A stage between these two layers could include some of the processing normally performed by the horizontal and bipolar cells.
Implementation of many retinal functions (eg, color encoding through different cone types and subsequent networks, rod-cone input balance and gain-control mechanisms that provide adaptation over an impressive range, and on- and off-pathway separation) cannot be replicated at the scale of normal retinal circuitry. Although technological hurdles remain, some of these may be solved by technology transfer from other areas of engineering. For example, logarithmic gain-control techniques are incorporated in semiconductor models of retinal processing, expanding the useful brightness range of such devices. Such technology could be built into a retinal prosthesis. Other functions may be created as the technologic capabilities and our understanding of the stimulation process increase. It may seem difficult to power an intraocular device without wires penetrating the sclera, but innovative technological advances in radio frequency and laser powering are already under development for similar applications.

Many concerns of a more physiologic nature exist, such as insertion of a device into the vitreous cavity, and attachment to the retina. An improperly positioned device could damage the retina during abrupt eye or head movements. Such concerns indicate the need to use thin, highly flexible substrate materials for an implanted array, and the importance that such an array be suspended over the retina, without touching it. Our experiments indicate that contact between the electrodes and the retinal surface is not required for stimulus perception. Moreover, there is an ongoing effort to improve surgical techniques using titanium tacks, cyanoacrylate glue, and adhesive polymers over the retinal surface. Each of these techniques could be used to stabilize an implanted device.

A visual prosthesis such as the one proposed here would restore or enhance vision in many people for whom no other treatment is expected to be available in the foreseeable future. Its applications could range from crude peripheral vision rehabilitation and improving mobility in midstage RP, to restoration of limited foveal vision in endstage RP and advanced age-related macular degeneration.

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