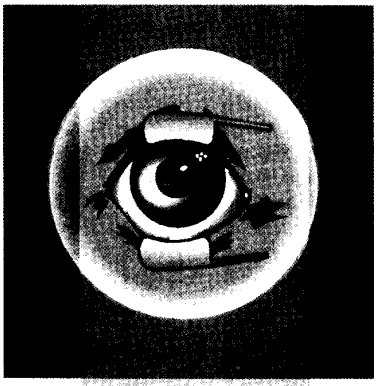

Visual Neuroprosthetics—Functional Vision for the Blind

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Recent progress in materials and microfabrication technologies have allowed researchers to reconsider the prospect of providing a useful visual sense to the profoundly blind. This will be accomplished by electrically stimulating their visual systems via an array of implanted microelectrodes. The techniques of the semiconductor industry have been employed to create electrode arrays with three dimensional architectures. These arrays are proving to be safely implantible into the visual parts of the brain of animals with little significant long term consequences. Thus, the tools of neuroprosthetics have been developed to the point that they will soon be used to validate some of the physiological foundations upon which artificial vision have been based. Validation of these foundations will accelerate the rapid pace of this research. If these physiological underpinnings can be shown to be solid, a demonstration of functionally useful vision in blind human volunteers may be possible within a five year time frame.

Overview

In a research laboratory at the National Institutes of Health, a 42 year old female volunteer who has been totally blind for the past 22 years of her life "sees" very primitive patterns of light [1]. At Johns Hopkins University, a blind man who has lost all visual sensation because of a progressive retinal disorder, retinitis pigmentosa, sees for the first time in many years a small flash of light [2]. While these preliminary experiments are providing blind volunteers with only rudimentary visual sensations, this research is rekindling the hope that researchers may be able to provide the profoundly blind with a functionally useful visual sense.

The research that may allow the realization of this dream is still in its infancy. However, recent technological breakthroughs in materials and in microfabrication technologies afford vision scientists, neurosurgeons, ophthalmologists and engineers the opportunity to investigate this problem. This article reviews the physiological foundations behind visual neuroprosthetics, and describes recently developed systems that may provide a useful visual sense to the profoundly blind.

Figure 1 illustrates the basic components that a cortically based visual neuroprosetic system will most likely contain. The system will require a video encoder to transform the visual world in front of a blind individual into electrical signals that can be used to excite neurons at some level of the visual pathway. This video encoder could be as simple as a miniaturized video camera mounted on a pair of eyeglasses. More likely, it will be a "silicon retina" that performs some of the image preprocessing functions of the human retina and will make the signals compatible with the neurons they are intended to stimulate. The signals must be delivered to electrodes that will excite neurons at an appropriate level in the visual pathway. This link will occur by either a hard-wired, percutaneous connection, or a telemetry link. Finally, the stimulating electrodes must be implanted into the visual pathway such that each electrode is able to excite only a small population of neurons in the vicinity of the electrode. Such a visual neuroprosthesis is expected to recreate a limited, but functionally useful visual sense in a blind individual who is using such a system.

Physiological Foundations of Visual Neuroprosthetics

An appreciation of the field of visual neuroprosthetics is predicated upon a basic level of understanding of a number of well documented physiological observations. These foundations are briefly described below.

1. Most forms of blindness are of retinal origin and leave the higher visual centers unaffected.

This observation is often unstated, but is key to a cortical approach to visual neuroprosthetics. The output neurons of the eye often degenerate in many retinal

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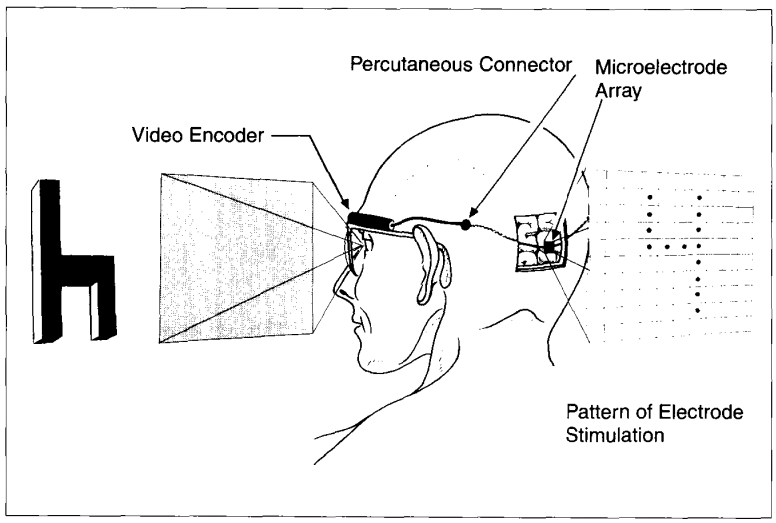


1. A possible visual prosthetic system would consist of a video encoder to transform optical images into electrical images, and an electrode array implanted at some level in the visual pathways for their focal stimulation by electrical means.

blindnesses. However, the neurons in the higher visual regions of the brain are usually spared this degeneration. The higher visual centers of sighted individuals provide a great deal of parallel information processing, and, in profoundly blind individuals, this computationally rich, hierarchically organized system lies fallow. If these higher visual centers can be stimulated with visual information in a format somewhat similar to the way they were stimulated prior to the development of total blindness, a blind individual may be able to use this complex neural computer to extract information about the physical world around him/her.

2. The visual pathways are organized in a rational scheme.

The organization of all sensory pathways is characterized by "maps" that transform neural activity at one level in the nervous system into neural activity at other levels. Usually, the mapping is associated with some form of information processing. In the visual system diagrammed in Fig. 2, there are a number of such maps. The light reflected from the objects in front of an observer (points "A" and "B" in this example) is projected by the optical elements of the eye onto an image on the back of the eye (the retina). This optical image is mapped into an electrical image by the photoreceptors of the retina. The cone photoreceptors decompose the colored image into three primary color maps (due to the absorption spectra of the three classes of cones) [3]. The photoreceptor electrical image is mapped onto the retinal ganglion cells (the retinal output). Spatial, temporal, and chromatic filtering of the visual message take place during this mapping operation. Next, the retinal output (the optic nerves) projects to a relay station (the lateral geniculate nucleus) where binocular mapping begins. Another network of neurons (the optic radiations) map the image onto primary visual cortex located on the rear surface of the brain. There are many other maps in higher visual centers of the brain, but not a great deal is known of these maps [4].

It is a general property of these mapping processes that the maps of higher brain centers appear to be more complex than the maps of lower centers. Thus, the map representing the output of the cone photoreceptors would be expected to more closely resemble the pattern of light that strikes the photoreceptors than would the pattern of activity at the retinal ganglion cell level or the pattern of neural activity in primary visual cortex. In spite of this increased complexity of visual maps, it has been known for decades that the maps at the levels of the retinal output and the input to the visual cortex are reasonably rational (at least on the low resolution scale that they have been studied to date). A rational mapping of visual space onto the neurons of the visual cortex, while not yet fully demonstrated, is one of the fundamental cornerstones upon which visual neuroprosthetics is based.

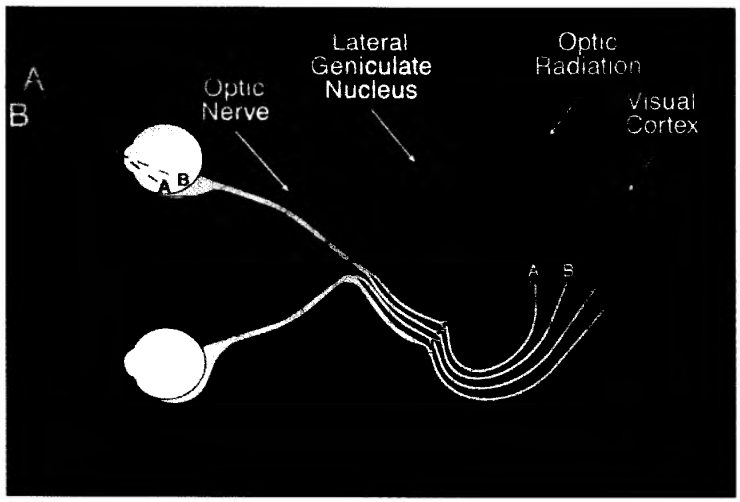
3. Electrical stimulation of neurons in the visual pathway evokes the perception of points of light (called phosphenes).

This general physiological observation has also been known for decades, and is not particularly surprising once one appreciates the mapping concepts described above. Since the visual world is mapped onto a certain region of the cerebral cortex, artificially stimulating the neurons in this region would be expected to produce percepts similar to those that are evoked by natural excitation: i.e., points of light. Such artificial stimulation can be achieved by the injection of very small electrical currents via external wires.

Recent experiments by researchers at the National Institute of Health [1] and others at Johns Hopkins University [2] have focused on obtaining a better understanding of these phosphenes. Both groups have evoked phosphenes in human volunteers using electrical stimulation via a very fine insulated wire (an electrode), but the site of the stimulation differed. The Hopkins researchers placed their electrodes on the surface of the retina while the NIH team placed 38 electrodes into the visual cortex. Both groups demonstrated that small electrical current pulses (in the microampere range), evoked the percepts of spots of light in front of the blind volunteers. Both groups verified that on the coarse scale studied, the perceptual maps were as expected. These results suggest that passing a two dimensional set of electrical currents through an array of electrodes, inserted into the visual system at an appropriate location, should create the perception of an array of phosphenes. Since the apparant brightness of these phosphenes can be controlled by modulating the currents through each electrode, this array could be used to produce a "pixelized" (or discretely represented) visual sense made up of a large number of adjacent phosphenes. The resulting visual experience might be something like that produced when looking at a football stadium scoreboard.

An important corollary to these experiments has developed over the past decade: it is possible to pass these relatively low amplitude currents through microelectrodes for long periods of time without appreciable damage to either the tissue into which the currents are injected, or the electrodes themselves [5].

4. The visual system is a highly adaptive neural network with a great capacity to make appropriate correlations between the sensed visual world and the physical world around the observer.



2. Schematic view of the visual pathways. Adjacent points in space (A, B) are mapped into adjacent images on the retina. This map is transformed into an electrical map that is projected onto the visual cortex, which then excites groups of cortical neurons that are adjacent to each other.

The plasticity of the visual system has been graphically demonstrated in experiments where observers viewed the world through inverting prisms for many months [6]. When first donning the prisms, the observers felt nauseous and had trouble maintaining balance. After a few days, they were able to move slowly in familiar environments and, after a few weeks, they were able to perform more complex motor tasks such as writing. In a few months, the subjects were able to ride bicycles and to catch thrown objects. This capability is only possible if the visual systems in these adult observers can be effectively rewired due to this completely abnormal visual stimulation. Thus, while the phosphene sense presented to a non-congenitally blind individual is expected to be a departure from the individual's previous visual experiences, it is hoped that this tremendous neural plasticity will allow quick reassociation of the "phosphene world" with the physical world.

Previous Attempts at Artificial Vision

The four observations described above provide a physiological framework around which a visual prosthetic system could be designed and built. As these observations have been generally appreciated for decades, it is not surprising that a number of scientists and engineers have used the observations to make pioneering attempts at providing a useful visual sense for the blind. Two notable efforts at developing an artificial vision system were undertaken in the 1960s and early 1970s.

Giles Brindley and his collaborators at Cambridge University developed a prototype visual prosthetic system and performed extensive tests with blind volunteers [7]. This system was based upon an electrode array that was placed upon the surface of the visual cortex. Each electrode was connected via its own lead wire to a small coil of wire. The coils of wire were mounted under the scalp over the skull of the blind volunteer, and allowed the passage of electrical current through each electrode via an inductive telemetry link. This telemetered approach minimized the likelihood of infection.

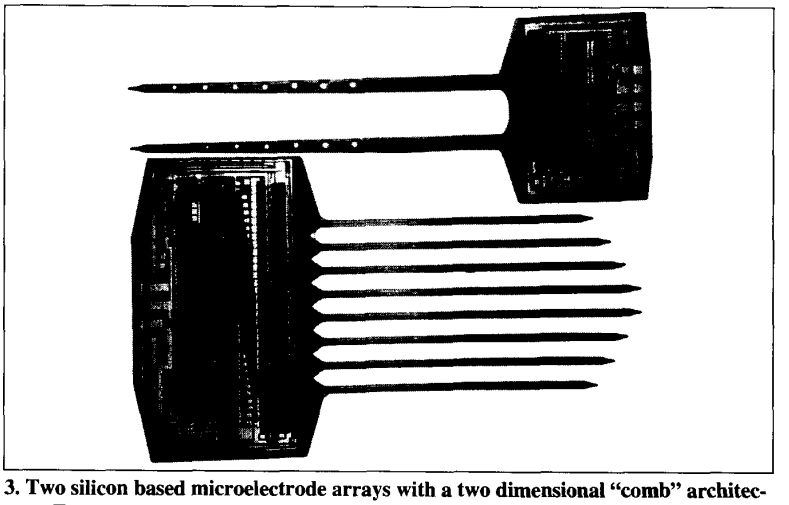
William Dobelle and his colleagues performed most of their work at the University of Utah and their findings were published somewhat later than Brindley's [8]. Dobelle also used an array of electrodes placed over the surface of the visual cortex, but, unlike Brindley, Dobelle used a percutaneous connector mounted behind the volunteer's ear to provide electrical access to the electrodes in his arrays. Dobelle performed a large number of acute experiments as well as a number of longer term semi-chronic experiments in blind volunteers.

Both Brindley and Dobelle made similar observations. Both groups demonstrated that individual phosphenes could be evoked by current injections through most of the electrodes in their arrays, and that the amount of current required to evoke a phosphene in each electrode was relatively constant during the entire period of the implantation. They both made the important observation that injection of currents through a number of electrodes could be used to produce complex patterns of phosphenes. However, neither endeavor resulted in the development of a useful visual prosthesis. Dobelle's subjects were able to interpret the current injections through six selected electrodes as Braille characters. These subjects could read the phosphene generated Braille characters faster than they could read them with their finger tips. This is hardly a useful visual sense and would certainly not warrant the risks associated with surgical implantation of an electrode array.

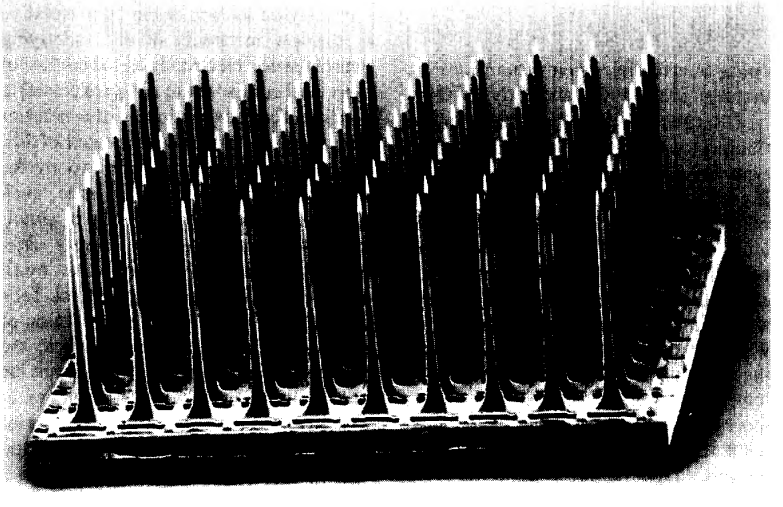
Moreover, Brindley's and Dobelle's experimental findings on minimal electrode spacing made the concept of a visual prosthesis based upon surface stimulation of visual cortex even less tenable. Because of the high resistivity of the membranes covering the surface of the brain (relative to the low resistivity of the underlying neural tissue), electrodes on the surface of the visual cortex would not be expected to produce focal excitation of the neurons underlying the electrodes. Because of this, the current levels required to evoke phosphenes were in the milliamp level, which precluded the possibility of simultaneous stimulation of too many electrodes (seizures could have been produced). Further, because surface stimulation excited a large population of neurons under the cortical surface, the large surface electrodes could not be placed too close to neighboring electrodes. Phosphenes evoked by currents injected through pairs of electrodes too closely spaced would often interact in a highly nonlinear way.

Artificial Vision in the 1990s

Brindley's and Dobelle's work made it clear that functionally useful artificial vision could not be possible until a means was found to provide much more focal stimulation of neurons in the visual pathway. Thus, much smaller stimulating electrodes than those used in the earlier studies were needed. These new generation electrodes would be about the same size as the neurons they are intended to stimulate. Kensall Wise at the University of Michigan applied the techniques used to build integrated circuits to the creation of small, high density electrode arrays [9]. This new generation of electrode array was built from silicon, and so it also contained integral signal processing circuitry. A mi-



3. Two silicon based microelectrode arrays with a two dimensional "comb" architecture. These electrode arrays are created using the IC photolithographic techniques. The arrays also contain integrated electronic circuitry. Photo courtesy of Kensall Wise, University of Michigan.



4. Scanning electron micrograph of the Utah intracortical electrode array. This "hair brush," three-dimensional architecture contains 100 electrodes, each of which is 1.5 mm long, 0.08 mm at its base, and tapers to a sharpened tip.

crograph of two of Wise's stimulating electrode arrays is shown in Fig. 3.

Because the techniques used to create these arrays are basically the two dimensional photolithograpic processes used by the semiconductor industry, the array has a two dimensional geometry and can best be described as a "comb-like" architecture, where the teeth of the comb contain the active electrodes. The teeth are intended to be implanted into the cortical tissues.

These new generation electrode arrays seem to have solved most the problems uncovered by earlier workers. The arrays are very small and the silicon from which they are fabricated is highly biocompatible. The arrays can be inserted into neural tissues, and the active electrode regions can be directly apposed to the neurons they are intended to stimulate to achieve very focal stimulation. However, there are other issues that must be addressed in the design of an electrode array that is intended to be used as the basis for a visual neuroprosthetic system. The integrated circuitry on the arrays must be hermetically sealed from the corrosive environment of the brain. Any parts of the array that are to extend outside of the neural tissues must be as unobtrusive as possible. Finally, there are three-dimensional architectural constraints that a cortical electrode array must satisfy. It is these considerations that have led researchers at the University of Utah to develop the cortical implant described below.

The Utah Intracortical Electrode Array

Rather than trying to adapt an existing technology to solve a particular problem, the Utah team first defined an electrode geometry that would be best suited to the task of cortical stimulation. Then they tried to fabricate such a geometry. The ideal array

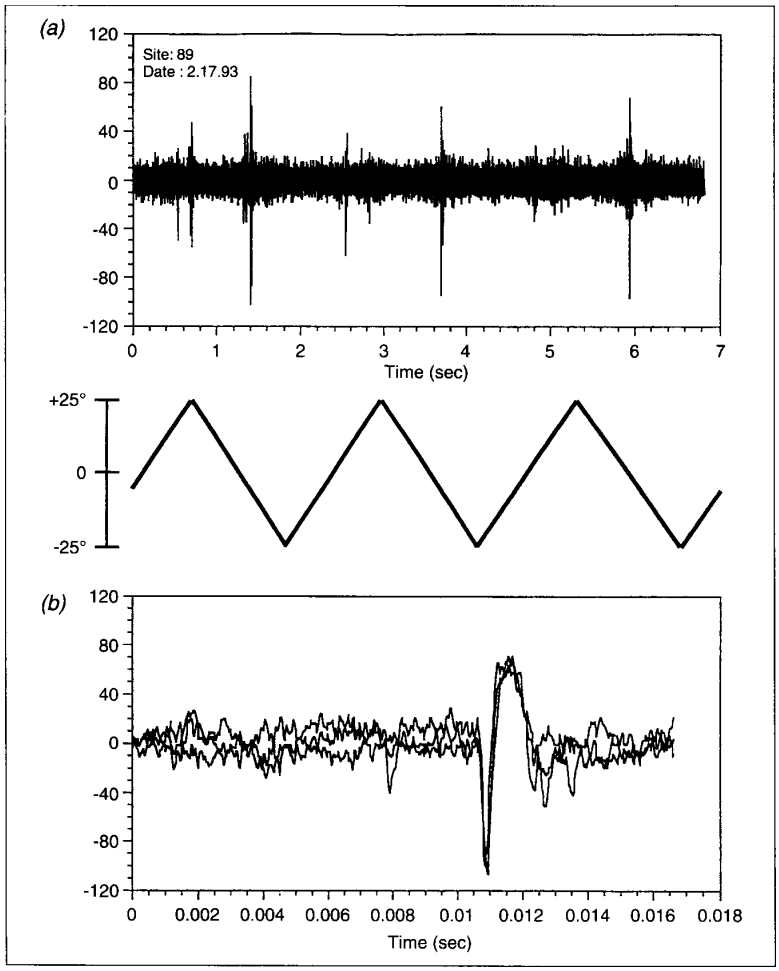
1. must be able to stimulate a two dimensional sheet of neurons that are coplanar with the surface of the visual cortex.

2. must have electrodes that penetrate through the surface and down to the level of the normal neuronal input to the visual cortex: the optic radiations. In humans, this region is about 1.5 - 2.0 mm below the cortical surface.

3. must have array components that are as unobstrusive as possible (applies to any component that extends beyond the cortical surface).

The electrode array architecture created by the Utah team is shown in Fig. 4. The techniques used in its manufacture has been described by Kelly Jones from our laboratory [10]. This array successfully achieves the conditions described above. The three-dimensional architecute of this array can be described as a "hair brush' (as opposed to the comb metaphor of the Wise electrode geometry).

The electrode geometry shown in Fig. 4 was designed for use in animal experiments. Each of the 100 needles in these arrays is 1.5 mm long and projects from a silicon substrate that can be as thin as 200 μm. The substrate is 4.2 mm on a side. The electrodes taper from an 80 μm base to a sharpened and metalized tip. Each electrode is electrically isolated from its neighboring electrodes by a glass dielectric that surrounds its base. Electrical access to each electrode is via a demultiplexing unit integrated onto the back surface of the array. However, as this circuitry has yet to be fully developed, we are currently making direct wire bond contact to a subset of 10 to 12 electrodes in the array, and con-



5. Light evoked photoresponses recorded with the Utah electrode array. The responses (top trace) were evoked by a vertical slit of light moving horizontally in front of a cat. The horizontal position of the slit is indicated in the middle trace. In the lower traces, three of the responses shown in the top have been superimposed and replotted on a faster time scale to demonstrate that these three large responses are probably from a single unit.

necting these insulated lead wires to a percutaneous connector. The entire structure, with the exception of the metalized tips, is insulated with 1 μm thick dielectric material.

Insertion of Electrode Arrays

Cortical tissue is relatively soft, but is covered with a tough membranous skin called the dura mater. Even when the dura mater is peeled back, it is a formidable task to implant a large number of electrodes into the cortex. While one or a few needles can be readily inserted, trying to insert a large number of electrodes only dimples the cortical surface. Thus, only partial insertion of electrodes around the perimeter of the array can be achieved. This problem has been solved with a pneumatically actuated inserter system, as designed, built, and evaluated in our laboratory by Patrick Rousche [11]. The inserter is capable of accelerating the array to high velocities and "shooting" it into the cortical tissues. The viscoelastic properties of the cortical tissue are such that complete insertion of the arrays is possible with little tissue insult.

Evaluation of Electrode Arrays

The biocompatibility of the Utah electrode arrays has been evaluated in a series of acute and chronic histological and electrophysiological experiments. Electrode arrays have been chronically implanted in cats for up to fourteen months.

Histology

Our histological studies of cortical tissues that have undergone electrode array implantation are most encouraging [12]. To summarize our findings, each electrode becomes encapsulated, but normal appearing neuron cell bodies are seen 10 to 20 microns from each electrode track. A fraction of the electrode tracks indicate that a small amount of local bleeding had occurred around the track, probably as a result of the implantation procedure. There is evidence of edema in the vicinity of the tracks, but the level has been judged to be non-problematic.

Electrophysiology

Perhaps the most compelling evidence of the biocompatibility of the materials and the benign nature of the implantation process is that evoked neural activity can be recorded with the electrode arrays in response to light simulation in specifi regions of the animal's visual space. An example of the evoked activity is shown in Fig. 5. The response is made up of action potentials from a number of cortical neurons, typical of a unit cluster response. In one cat that had been implanted on a chronic basis, we were able to record similar cluster responses (but manifesting a poorer signal-to-noise ratio than that shown in Fig. 5) for up to 14 months (at which time the animal was sacrificed). Craig Nordhausen, a graduate student in our laboratory, has conducted a complete study of the acute recording capabilities of the Utah intracortical electrode array [13].

Psychophysical Experiments

The visual sense that stimulation of the visual cortex is expected to produce will differ in many respects from that of sighted individuals. Since pairs of adjacent electrodes will not be able to be positioned so close that current stimulation through both will produce two completely contiguous phosphenes, the visual sense is likely be somewhat pixelized (i.e., composed of a large number of very closely spaced phosphenes). Further, as first generation arrays will be limited in the number of electrodes they contain, the scope of the visual sense evoked will be far from the panoramic one of sighted individuals, but will be much more of a "tunneled" nature. The size of this tunneled sense will be limited by the radius of curvature and arc length of a cortical gyrus (bump on the brain surface). Based upon a number of anatomical and physi-

6. Photograph of the portable, pixelized vision emulator, which is composed of a video camera and video monitor mounted on a pair of ski goggles. The monitor is masked with perforated foil, which simulates the pixelized visual sense that the blind subject might experience when stimulated via the Utah intracortical electrode array.

ological criteria [14], it is unlikely that electrodes could be usefully spaced closer than 300-400 μm. Thus, the visual sense created with a first generation visual prosthesis might consist of about 625 phosphenes distributed over a 1.7 degree visual angle (about the slze of one's thumb nail at arms length). When confronted with these discouraging quantitative considerations, one wonders if such a limited and pixelized visual sense could be of any use to a blind individual. Thus, before electrical stimulation of the visual cortex could be considered to be a viable approach, experiments would be needed to evaluate what kind of visual task performance can be achieved with a very limited pixelized visual sense.

Using a portable pixelized vision emulator (Fig. 6), Kenneth Horch and Kichul Cha have recently performed a number of experiments to address this question. The emulator is described in [15], and consists of a miniaturized, closed circuit video system mounted on a pair of ski goggles. The only visual input to the wearer of the emulator is via a miniaturized video monitor covered with a perforated foil mask containing up to 1024 holes. Optics in front of the monitor limit the size of the perceived pixelized image to 1.7 degrees of visual angle and a lens in front of the video camera controls its acceptance angle. Scanning of objects in front of the wearer is accomplished by head movements. Using this device with a foil mask containing 625 perforations, student volunteers are able to read text out loud from a computer screen (at a rate about 2/3 that at which they can read without the emulator) [16]. Much of the work we have done with the simulator has been focused on determining the degree of visually guided mobility that can be achieved with such a limited pixelized visual sense. We have built a programmable maze through which student volunteers must navigate, while using only this limited pixelized visual input. The maze is formed by a large number of curtains that can be raised or lowered by the experimenter. After each traversal of the maze, curtains are adjusted and a new path created. The index of visually guided mobility is the time required to navigate the maze. After about 30 trips through the maze, the learning curves of the student volunteers flatten. With only 625 pixels of visual information, the subjects were able to navigate through this highly complex visual environment at a speed close to the speeds attained with normal vision. More importantly, they navigate this complex environment with high levels of confidence, as described elsewhere in [17].

Discussion

While the focus of this article was electrical stimulation of the visual cortex, a thorough exposition of artificial vision must also consider work directed at electrical stimulation of the ganglion cells of the retina. The concept being pursued by researchers at Johns Hopkins University [2] and at MIT and Harvard University [18] is to implant a visual prosthesis directly on the surface of the retina of a blind indvidual. The implant is proposed to contain an array of photodetectors on its front surface and an array of electrodes on its rear surface. Signal processing electronics will also be incorporated into the implant. In support of this concept, the Hopkins researchers have stimulated, with a single microelectrode, the retinas of a number of patients who have advanced retinitis pigmentosa. As expected, electrical stimulation of the retinal ganglion cells evoked phosphenes in these volunteers [2].

This retinal work is also in its infancy but it has a number of aspects that are particularly attractive. The coupling of electrodes and photosensors in a single implant could take advantage of the image forming properties of the eye (i.e., the cornea and lens) to transduce visual images incident upon the photodetector array into electrical signals. This process could eliminate the need for an external video camera. The surgical implantation of a retinal device might be regarded as being less traumatic than a cortical implant. Since the retinal implant is closer to the visual image than is a cortical implant, the retinal map would be expected to be more rational than a cortical map.

A retinal implant also has a number of considerations that would tend to argue against this approach. Most importantly, most retinal degenerations produce retinal ganglion cell degeneration. If this is the case, a retinal implant might have applicability in only a very small number of profoundly blind individuals. Further, the retina is an extremely delicate tissue (0.5

mm thick), which is likely to react catastrophically if a chronic implant of any significant size and mass were to be placed against and attached to it. If the extraocular eye muscles are not immobilized, the saccadic motions of the eye could be large enough to produce trauma to the retina where the implant is attached. Finally, the retinal ganglion cell map is only rational if one is able to stimulate the retinal ganglion cell bodies. As the optic nerve fibers that emanate from the retinal ganglion cell bodies and exit the retina at the optic nerve head are located between those cell bodies and the surface electrodes, a technique by which the retinal ganglion cell bodies can be stimulated with currents that do not stimulate the optic nerve fibers will have to be developed. This last problem is likely to present quite an interesting challenge.

It is clear from this discussion that demonstrating functional artificial vision in a blind volunteer is still many years away. While some progress has been made in terms of phosphene characterization in blind human volunteers, electrode array development, implanting such complex structures in the brain, and in the biocompatibility of these cortical implants, there are many issues that must be resolved before chronic human implantation of high density electrode arrays can be considered. Animal behavioral experiments should provide us with a better understanding of the problem of electrode interactions. Once groups of animals have been trained to press levers when they perceive a point of light, we can inject electrical currents into their cortices rather than present them with a visual stimulus. If the animal presses the lever, the electrical stimulation is presumably evoking a percept similar to that produced by visual stimulation. These experiments will allow us to measure phosphene thresholds. Similar current injection with animals trained to respond to two spots of light will provide better criteria for spacing of electrodes in cortical arrays.

With the development of these new three-dimensional electrode arrays, we will soon be in a position to explore the fundamental physiological foundations of artificial vision. Specifically, just how precise is the mapping of visual space onto the visual cortex? How stable are the phosphene thresholds on a day by day basis, even when the visual cortex is being stimulated as much as 16 hours per day? How far apart can a pair of electrodes be positioned and still produced contiguous phosphenes. Does patterned stimulation (passing a set of currents through a preselected set of electrodes) produce patterned percepts?

When these fundamental questions have been answered, the intellectual barriers to a visual prosthesis based upon electrical stimulation of visual centers will be removed, and the question of providing useful vision to the blind will be "when" rather than "if". An optimistic view of the pace of research in artificial vision must be based upon the results of these physiological experiments. It is not unreasonable to expect that an electrode array that could provide a useful visual sense to a blind volunteer could be implanted within the next five years., and commercial visual prosthetic systems could be available after the turn of the century.

Acknowledgments

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Richard A. Normann is Professor and Chair of the Department of Bioengineering at the University of Utah, where he has conducted basic research on information processing in the vertebrate retina and visual cortex and applied research in the area of visual neuroprosthetics. The Bioengineering Department has recently been awarded a Whitaker Development Grant to create an academic program in "Bio-based Engineering." The goal of this program is to bring some of the organizational principals of biological systems into the discipline of Bioengineering and to apply some of the problem solving strategies of biological systems to the problems of conventional engineering and medicine. Professor Normann can be reached at the Department of Bioengineering, 2480 MEB, The University of Utah, Salt Lake City, UT 84112.

References

1. **Vallabhanath P, Bak MJ, Hambrecht FT, Kufta CV, O'Rourke D, Schmidt EM:** Feasibility of an intracortical visual prosthesis for the blind: II. Visual sensations produced by cortical stimulation. *Soc. Neurosci. Abstr.*, 18, Part 2, 1396, 1992.

2. **Humayun MS, Propst RH, Hickingbotham D, deJuan Jr. E, Dagnelie G:** Visual sensations produced by electrical stimulation of the retinal surface in patients with end stage retinitis pigmentosa (RP). *Assoc. Res. Vis Ophthal. Abstracts* 835, 1993.

3. **Normann RA, Perlman I, Hallett PE:** Cone photoreceptor physiology and cone contributions to color vision. In: Gouras P (ed): *The Perception of Color*. In: *Vision and Visual Dysfunction*. Volume 6. MacMillan Press, 1991.

4. **Hubel D:** *Eye, Brain, and Vision*, Scientific American Library, 1988.

5. **Agnew WF, McCreery DB (eds):** *Neural Prostheses*, Prentice Hall, 1990.

6. **Dolezal H:** *Living In A World Transformed*, Academic Press, 1982.

7. **Brindley GS, Lewin WS:** The sensations produced by electrical stimulation of the visual cortex, *J. Physiol* 196: 479-493, 1968.

8. **Dobelle WH, Mladejovsky MG:** Phosphenes produced by electrical stimulation of human occipital cortex, and their application to the development of a prosthesis for the blind. *J. Physiol* 243: 553-576, 1974.

9. **Wise KD, Najafi K, Ji J, Hetke JF, Tanghe SJ, et al:** Micromachined silicon microprobes for CNS recording and stimulation. *12th International Conference of the IEEE Engineering in Medicine and Biology Society 5:* 2334-2335, 1990.

10. **Jones KE, Campbell PK, Normann RA:** A glass/silicon composite penetrating intracortical electrode array. *Annals of Biomedical Engineering* 20: 423-437, 1992.

11. **Rousche PK, Normann RA:** A method for pneumatically inserting an array of penetrating electrodes into cortical tissue. *Annals of Biomedical Engineering* 20: 413-422, 1992.

12. **Schmidt S, Horch KW, Normann RA:** Biocompatability of silicon based electrode arrays implanted in feline cortical tissue. *J. Biomedical Materials Research* 27, 1393-1399, 1993.

13. **Nordhausen CT, Rousche PJ, Normann RA:** Optimizing recording capabilities of the Utah Intracortical Electrode Array. *Brain Res*, 637, 27-36, 1994.

14. **Normann RA:** A penetrating, cortical electrode array: design considerations. *1990 IEEE International Conference on Systems, Man, and Cybernetics* 918-920, 1990.

15. **Cha K, Horch KW, Normann RA:** Simulation of a phosphene-based visual field: visual acuity in a pixelized vision system. *Annals of Biomedical Engineering* 20, 439-449, 1992.

16. **Cha K, Horch KW, Normann RA, Boman DK:** Reading speed with a pixelized vision system. *J. of the Optical Society of America*. 9:673-677, 1992.

17. **Cha K, Horch KW, Normann RA:** Mobility performance with a pixelized vision system. *Vision Research* 32:1367-1372, 1992.

18. **Risso, J:** Development of a silicon retinal implant. *Assoc. Res. Vis* Ophthal. Abstracts, *1994.*