Current Status of Artificial Vision by Electrocortical Stimulation

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ABSTRACT: The history of the provision of artificial vision by electrocortical stimulation has its origin in observations over 50 years ago. However, the realistic modern stimulation of human visual cortex is only 20-years-old. No useful device has been devised as yet and it therefore remains purely experimental. The primary objective of such a prosthetic device is that of independent mobility. This would require the appreciation of half-tone pictures, the detection of depth and discontinuities in outlines, and a significant quality of resolution. Some of the problems which threaten resolution in such a device and the factors which must be overcome in order to achieve a useful visual prosthesis are discussed.

RÉSUMÉ: Mise à jour sur la vision artificielle par stimulation électrocorticale. L'historique de la vision artificielle par stimulation électrocorticale tire son origine d'observations faites il y a plus de cinquante ans. Cependant, l'approche moderne de stimulation du cortex visuel humain a seulement vingt ans. Aucun appareil efficace n'a encore été inventé et ce procédé demeure purement expérimental. L'objectif principal d'une telle prothèse est la mobilité autonome. Pour atteindre ce but, le prothèse doit fournir une appréciation des demi-tons, de la profondeur et des interruptions dans le contour des objets ainsi qu'une résolution de bonne qualité. Nous discutons de quelques uns des problèmes qui ont trait à la résolution dans ce type d'appareil et des obstacles qui doivent être contournés pour arriver à réaliser une prothèse visuelle efficace.

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Early Observations on Visual Cortical Stimulation

The earliest clearly recorded observations on the stimulation of human visual cortex in awake subjects came from the German neurosurgeons in the 1920's.[1-3] Their observations disclosed the fact that motionless dots of light were produced in the contralateral visual field as a result of punctate stimulation of visual cortex. Penfield and his colleagues, in their extensive stimulation studies, made similar observations later, among many others.[4,5] In the 1950's some suggested making use of these dots to provide some type of useful information for blind patients. Thus it was that Krieg suggested a number of methods for alleviating the handicap of blindness, among which was interfacing some type of transduced light perception to electrical stimulation of the occipital cortex.[6] In 1955 Shaw made a similar suggestion of transducing light received by a photocell into electrical stimulation which by transformer coupling would be applied to electrodes on occipital cortex. His "system" was attractive enough that he applied and received for it a United States patent number.[7]

The 1960's witnessed actual application of electrical stimulation to the visual cortex of man. In 1962 Button and Putnam reported the effects of transiently stimulating three individuals with the use of fine wires inserted into the visual cortex through twist drill holes over the occipital regions.[8] One of the patients was able to follow a light source with a hand held photocell as a result of transduction of the light signal to electrical stimuli applied through these wires.

Brindley's Observations

The systematic exploration of the feasibility of a visual prosthesis by electrocortical stimulation was undertaken by Brindley in the early 1960's and continued on until the present time with collaboration of a number of colleagues. In 1964 he calculated that 50 channels of on/off lights, appropriately placed, should allow an individual to read 10 letters in one fixational pause and that 600 channels would allow a normal reading rate.[9] He also demonstrated the feasibility of transcutaneous stimulation by radiotelemetry.[10] In 1968 he and Mr. Lewin reported the preliminary results which had been obtained from stimulating a blind patient with an 80 electrode array applied to her right occipital cortex.[11-13] From these studies they showed that the dots of light, or "phosphenes", were all projected to the contralateral

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visual field, that there was a rough approximation of the visuotopic organization of the phosphenes to the classical map of Holmes[14] but with definite incongruities, that two phosphenes may be distinguished from one another resulting from stimulation of cortical points at least as close together as 2.4 mm, that most of the phosphenes are colorless and small but may have various shapes and sizes, and that a number of electrodes may be stimulated at a given time to construct simple recognizable patterns. A number of other publications by Brindley and his colleagues verified these original preliminary observations, examined the stability of phosphenes over time, examined the specific visuotopic representation of the phosphenes, and discussed the various methods of mapping phosphene space.[15-21]

Some of the above observations were made on a 64-year-old man who had been blind for 30 years who received an implant in 1972 over both occipital lobes.[16] The phosphenes in this second patient were large and hence not easily usable. Thus only limited information was provided over the initial patient. A third implant was placed over both occipital lobes of the initial patient, after the initial implant had been removed. Only fragmentary observations have been reported with respect to this patient.[22]

Observations in the 1970's

Following the work of Brindley the decade ended with an international conference on visual prostheses.[23] Following this, there were three main avenues of inquiry into a potential visual prosthesis. Brindley and his colleagues continued their experiments as noted above. The National Institutes of Health established the Neural Prosthesis Program (formally the Sensory Prosthesis Program) under the directorship of Drs. K. Frank and T. Hambrecht with the aim of examining a variety of basic research aspects involved with chronic cerebral stimulation.[24] Thirdly, Dr. William Dobelle led the research in the Division of Neuroprostheses in Dr. Kolff's Department of Artificial Organs at the University of Utah. The thrust of this program was to follow the lead of Brindley and his colleagues in directly examining the feasibility of developing an electrocortical visual prosthesis.

The contracts of the Neural Prosthesis Program has established a large base of research data pertaining to the biocompatibility of various metals, the comparisons of different types of electrode configurations, the materials to insulate these electrodes, the electrochemistry of the electrode-brain interface, and the establishment of "safe limits" of chronic stimulation as determined in experimental animals.[25-29]

Dobelle and Mladejovsky and their team travelled to various neurosurgical centers in North America where patients were operated upon under local anesthesia for a variety of conditions.[30] These instances provided opportunities, albeit for short periods of time, to stimulate the visual cortex of sighted patients and gather information preparatory to experiments on unsighted volunteers.

In 1973 two blind patients, having been recruited four years earlier, underwent acute experimental stimulation over a 72-hour period during which many of the observations made by Brindley were confirmed.[31] The following year another patient was implanted transiently for seven days, but unfortunately very little useful information was derived. This led to a realization that some type of chronic (weeks to months) hard-wired methodology must be developed in order to maximize the results of such stimulation. A pyrolytic carbon pedestal was utilized for both cochlear[32] and visual prostheses.[33] Two such 72 pin pedestals were inserted into blind volunteers in the summer of 1975, one of which was removed three months following implantation and the other over 10 years later. When they were initially implanted it was considered that they might be able to be used for a few weeks or hopefully even for a few months. It was not considered at the time that they might be utilized for years.

Experiments were conducted periodically over the 10 years in sessions of approximately two hours each and up to as many as three sessions per day. Threshold experiments have shown approximately a 10 percent variation from hour to hour and day to day, little more than the limits of resolution of threshold. The average threshold was 1.8 mA, zero-to-peak (rectilinear, biphasic, balanced waveforms), with a range of 0.8-5.2 mA. Mapping experiments have been similar to those of Brindley with the majority of the phosphenes clustered around the vertical meridia of the visual fields and a relative paucity of phosphenes around the peripheral part of the horizontal meridian, in keeping with the predictions of the classical visuotopic maps. Using six appropriately arranged phosphenes a "phosphene braille cell" was used to examine the rate of spatial transfer of information.[34] The patient, who was a poor tactile braille reader, "read" faster and more accurately using the phosphene braille cell than by tactile braille. Further, frame rates of up to four per second were able to be distinguished by the patient without blurring. Using a TV camera on a joy stick operated by himself, the patient was able to recognize one inch wide white lines on a black background as having a horizontal or vertical orientation. Other experiments have examined the effect of altering various stimulus parameters on phosphene threshold[35] and brightness modulation.[36]

Ideal Visual Neuroprosthesis

The ideal visual prosthesis would involve a number of relatively easily identifiable criteria. First, it would be a mobility prosthesis. Second, it should be a prosthesis which would use whatever current visual pathway apparatus that existed in order to provide the artificial vision. Third, it would as closely as possible duplicate normal vision.

One of the initial thrusts for a visual prosthesis was to provide the blind with the ability to read[9-12,15] but in fact this author feels that the technological advances for the provision of reading material for the blind has been sufficient in the last two decades to preclude reasons for justifying the fabrication of a prosthesis in order to achieve reading alone. The speech synthesizer to computer is the best available reader and will undoubtedly undergo fine tuning in both its technical aspects as well as a reduction in costs and almost certainly will be available to most of the blind community before the end of this century. Nearly all individuals associated with this field have emphasized the fact that it is mobility and orientation which are the two most important aspects leading to independence in the unsighted individual. Thus, the real requirement of the twentieth and twenty-first centuries is that of a mobility prosthesis, not a reading prosthesis.

Most of the devices which have been utilized for aids to the blind for independence have utilized the use of other sensory systems. The sonar, or laser, cane which was of great interest in the last decade is heavy, bulky, and costly and has never been widely accepted by the blind and has never really provided an improvement over the long cane which is still the most useful device.[37] Such devices which use other sensory systems interfere, distract, and decrease the usefulness of information coming through those systems as a result of the sensory substitution. Thus, any device which would take advantage of whatever remaining visual anatomical pathways exist would have a great advantage over some other form of sensory substitution.

The prosthesis must be one which is involved with half-tone reproductions. This involves not simply an "on-off" system of dots but rather pictures which can be composed of a grain which can be brightness modulated. Only by brightness modulation can the detail of shadows and facial features be provided.

The ideal "grain" of the phosphene field should be sufficiently fine that resolution allows the appropriate recognition of not only gaps and discontinuities (e.g. curbs, trees, doorways, drawers, etc.) but also the fine features of shadow provided by brightness modulation. The grain of the phosphene field would be no different than the grain of photographic film, scoreboards at the end of athletic fields, or that of pictures in various types of newsprint. Such a field must be homogeneous and ideally should consist of dots which are small, densely packed, and of uniform size and shape. If such a phosphene field could be produced, then there is no doubt that ambulatory independence and a highly useful degree of artificial vision would have been achieved.

FEASIBILITY OF AN ELECTROCORTICAL VISUAL PROSTHESIS

A number of potential problems and concerns have arisen which certainly threaten the potential feasibility of the development of artificial vision from electrocortical stimulation. These concerns can be grouped into engineering and biological categories.

Engineering Concerns

The major obstacle in the engineering design of such a prosthesis would be that of the transfer of information transcutaneously. The alternatives consist of telemetry or direct hard wiring. If such an eventual prosthesis had hundreds of phosphenes then the information on these phosphenes, particularly regarding brightness modulation, would include for each individual phosphene a number of stimulus parameters for any given brightness. The task of the RF transfer of a large number of parameters pertaining to a given dot, and of hundreds of dots in real time, is almost unimaginable. If a percutaneous pedestal of some type can be utilized, such as those referred to above, then the complexity of this task is markedly reduced.

The use of these pedestals in a rather wide variety of neural prosthetic devices will presumably allow the question to be answered within the next two or three decades as to whether such hard wiring is possible on an indefinite basis.

Biological Concerns

Brightness Modulation The question of brightness modulation is an important one for any consideration of half-tone pictures. The task of relating, and encoding in computer memory, the relationships between the brightness of large numbers of electrodes and the alterations in parameters bringing about this brightness is enormous. This will require tremendous numbers of hours of research using psychophysical methodology. Only fragmentary observations exist at the present time on this question[11,12,31,36] and hence this avenue of exploration awaits a thorough systematic exploration.

Brightness modulation may occur not only by altering the levels of gray in individual dots but by varying the density of very small dots, as occurs in many of the half-tone pictures in newsprint. It would appear inconceivable to this author at the present time that sufficient numbers of densely packed dots will be able to be achieved from cerebral stimulation to allow the luxury of brightness modulation in this way.

Homogeneity of the "Phosphene Field" At the present time only surface stimulation has been systematically explored and as would be predicted on the basis of the classic visuotopic maps, the lateral part of the visual field has a paucity of phosphenes. If the whole phosphene field is to be filled out there must be some way to gain access to the visual representation buried in the calcarine fissure and secondary sulci. A number of possibilities exist with respect to how this might be achieved.

In theory a prosthesis might exist from stimulating the visual pathways anywhere from the retina through to the visual cortex. Unfortunately, the easiest access, *i.e.*: the retina, is precluded because most blindness is on the basis of a loss of the anterior pathways. Certainly there are some cases in whom the ganglion cells remain intact and would be available for stimulation but these represent the minority. There are not many observations on stimulation of the optic radiations. Those that exist indicate that the phosphenes might be very large.[38-40] Large phosphenes would markedly decrease resolution. Perhaps with newer methods of microstimulation such phosphenes might be small enough to be usable but this remains unclarified.

Phosphene Interactions Both Brindley's and Dobelle's experiments have indicated that phosphene interactions occur.[11,12,31] These interactions which may result in the addition of spurious unwanted phosphenes or the deletion of phosphenes when multiple phosphenes are presented together, decrease the resolution of patterns. If such interactions were numerous and unpredictable then resolution would suffer.

Multiplicity of Phosphenes Multiple phosphenes also have been shown to occur from punctate cortical stimulation by Brindley and Dobelle and their colleagues. If the multiplicity is something which is present and cannot be precluded by alteration of stimulus parameters, then this represents a significant deterrent to optimal resolution. Preliminary results would indicate that the most powerful presently recognized parameter for brightness modulation is current. Unfortunately, current is nearly linearly related to the production of multiplicity of phosphenes.[41]

Phosphene Grain The grain of the phosphene field is the most important determinant of the resolution. The ideal field, as noted above, would consist of densely packed, homogeneous, small phosphenes of uniform size and shape which are capable of brightness modulation. Such small phosphenes may be produced from cortical stimulation. It is also known that there is theoretically sufficient primary visual cortex in man to support the production of sufficient numbers of phosphenes for an adequate prosthesis.[42] However, perhaps more intuitive than theoretical, there is reason to suspect that intracortical microstimulation might provide smaller phosphenes in addition to other advantages (see below). Further, on the basis of the foregoing, it would appear that some type of stimulation below the cortical surface, *i.e.*, intracortical or subcortical, would be required in order to fill out the whole of the phosphene field. At the present time experiments, examining the feasibility of such intracortical stimulation, are being undertaken with Dr. Hambrecht and his colleagues of the Neural Prosthesis Program, in sighted patients undergoing operations under local anaesthesia. The preliminary observations from these will be reported soon, but certainly it can be said that very small phosphenes can be produced from within the cortex at very small stimulating strengths *i.e.*, tens of microamperes. In spite of these encouraging early experiments, an open mind must be retained as to the final widespread merits and feasibility of the use of this method of stimulation.

Universality of Use

Can such an envisioned prosthesis be utilized for all blind patients? Based on the fragmentary data available, it would appear that the longer that one is blind, the less likely is the possibility of the production of ideal small phosphenes from cortical stimulation.[8,18,31] Thus it would appear that the longer that blindness has existed the larger might be the phosphenes resulting from such punctate stimulation. Further, on the basis of one of the patients of Button and Putnam as well as personal observations, it would appear that the extreme of this is realized in those who are blind from birth in which the concept of light cannot be appreciated and in whom it would appear that visual cortical stimulation will not result in light production of any kind, much less in useful phosphenes. This may be relatively unimportant as 65% of newly blinded individuals are over the age of 65 years,[37] *i.e.*, having full memory of visual imaging and having become blind "recently".

Future Directions

The biological problems at present represent definite potential problems, but indeed these problems are testable for the most part. The research is highly interdisciplinary, requiring expertise from a number of engineering, computer, and biological fields. Because of this it is extremely time consuming, labour intensive, and expensive. It is because of this requirement for a large critical mass of disciplines, e.g., physiological, psychophysical, computer engineering, materials engineering, and clinical medical and expense, that the information pertaining to the feasibility of such a prosthesis has been so slowly accumulating. In this regard it is rather ironic that the visual prosthesis which was embarked upon as the initial neural prosthetic device has lagged behind the other neural prostheses relating to functional neuromuscular stimulation, bladder stimulation, and auditory stimulation. The reason for this is obvious, however, in that the complexity of this type of research and the research output related to a given neural prosthesis are inversely correlated. For this reason, therefore, it would be predictable that the auditory prosthesis, whether single channel or multiple channel, would eventually lead the field down the path of feasibility determination.

As outlined some years ago, the field cries for good systematic evaluations of intracortical stimulation.[43] Hopefully, the current work in this field, in collaboration with the investigators from the Neural Prosthesis Program of the National Institutes of Health, will provide relevant information on both intracortical and immediate subcortical stimulation of visual cortex and that with the ground work already laid for this that significant advances towards a realization of a visual neural prosthesis will have occurred by the end of the century. It is unlikely that this will happen, however, unless large interdisciplinary groups of research workers are able to be established which would provide the critical mass of expertise to allow productive self-sustaining research. The hardware required for such a prosthetic device is available and improving continually as reflected in particular in the miniaturization of cameras, computer chips, and power sources. There are many areas of overlap between the research required in visual prosthetic work and in the other much larger field of artificial organs in general and of course much more specifically in the field of neural prostheses. Nowhere is the lack of this type of research more evident than here in Canada.

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