Rewiring the brain – creating artificial vision

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***Abstract*—The current state of visual prostheses progresses rapidly. In this essay three approaches to a visual prosthesis are discussed: an epiretinal implant, a visual prosthesis which stimulates the optic nerve, and a visual prosthesis which stimulates the lateral geniculate nucleus. While the epiretinal implants are currently the most advanced visual prostheses available, I think a visual prosthesis stimulating the lateral geniculate nucleus has the greatest potential, especially when you also keep applications for people with healthy vision in mind.**

I. Introduction

OUR visual system is quite advanced: it has very good lenses, it is self cleaning, it can automatically focus, it can track moving objects, there is image stabilisation, and it works at widely different light levels. No wonder it is one of our most important sensory organs. Vision allows us to perceive the world, recognize shapes, colors and movement. Almost half of the cerebral cortex is used for visual processing [1].

Losing the ability to see is a severe handicap for the rest of someone's life. Someone would need to relearn a lot of casual tasks, relying more and more on touch and sound. It would be a lot more convenient if we could restore the vision (partially) for someone who got blind.

Luckily, a lot of effort is being put into the development of a device which could do just that. A visual prosthesis is a device which electrically stimulates parts of the optical pathway, to generate visual sensations, "phosphenes".

This essay shows several approaches to a visual prosthesis, and discusses which method has the greatest potential, for blind patients but also for people with healthy vision. It is organized as follows: In Section II, we start with an overview of the eye and the retina. In Section III several approaches to a visual prosthesis are listed, including their advantages and disadvantages. In Section IV the approaches are discussed, and everything is concluded in Section V.

II. Overview of the eye

The eye is the receptor organ for the visual system. It is enclosed by three layers of tissue: the *sclera*, the *choroid*, and the *retina*. An overview of all components of the eye, and the different layers of the retina can be seen in Figure 1. This document will not cover the anatomy of the eye in depth, and mainly focus on the retina.

A. Anatomy of the eye

The sclera is the outermost layer, and it is made of a tough fibrous tissue. The anterior part of the sclera is transparent, allowing light to pass through. This part of the sclera is called the *cornea*.

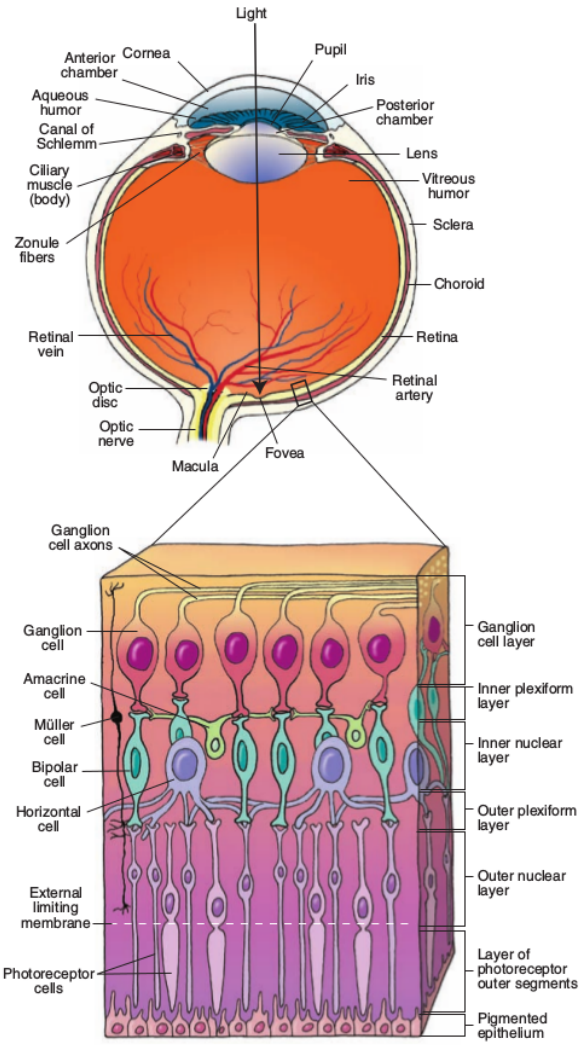

Fig. 1. The anatomy of the eye and the different layers of the retina [2]. Picture courtesy of Siegel et al.

The choroid is the middle layer, and is highly vascularized. The iris is also part of this layer. The iris contains the pupil, the central opening where light goes through. The size of the pupil is neurally controlled by the circular and radial muscles of the iris.

The inner most layer is called the retina, and all phototransduction happens in this layer. The point where the optic nerve exits and the blood vessels supplying the eye enters is called the *optic disc*. There are no photoreceptors in this spot, and therefore it is often called the blind spot. Lateral to the optic disc lies the *macula lutua* (or simply macula). This region is responsible for the central vision (as opposed to the peripheral

vision).

In the center of the macula there is a small depression called the *fovea*. There are a lot of *cones* in this spot, and the layers of cell bodies and processes that overlie the photoreceptors in other regions of the retina are displaced in the fovea. This results in a very high visual acuity, and there is no other region in the eye which matches the visual acuity of the fovea [2].

B. Layers of the retina

The retina has several layers each with their own function, starting from the most outer layer: [2]

- **Pigment epithelium layer**. Contains cuboidal cells that contain *melalin*. These cells are responsible for the nutrition of the photoreceptors (mainly glucose and essential ions). Melalin is a black pigment that absorbs any light on the cell, to prevent scattering of light which would result in a less sharp image.
- **Photoreceptor layer**. This layer contains the light sensitive portions of the rods and cones, the photoreceptor cells. In most regions, the amount of rods outnumber the amount of cones, with the exception of the fovea.
- **External limiting membrane**. The processes of the photoreceptor cells pass through the external limiting membrane. This region also contains the processes of *Müller cells*.
- **Outer nuclear layer**. Contains the cell bodies of the rods and cones.
- **Outer plexiform layer**. In this layer synaptic interaction between photoreceptors and *bipolar* and horizontal cells takes place. It contains the axonal processes of the rods and cones, processes of horizontal cells, and dendrites of bipolar cells.
- **Inner nuclear layer**. The cell bodies of *amacrine cells*, horizontal cells, and bipolar cells lie in this layer. The horizontal and amacrine cells are called association cells, and function as interneuron.
- **Inner plexiform layer**. This is another layer where synaptic interaction takes place between different retinal cells. This layer contains the axons of the bipolar cells, the processes of amacrine cells and the dendrites of ganglion cells.
- **Ganglion cell layer**. All ganglion cells lie in this layer. Their axons form together the optic nerve, transmitting the visual information to the central nervous system.
- **Optic nerve layer**. This layer contains the axons of the ganglion cells.

C. Cones and rods

Rods and cones are the two types of photoreceptors in the retina. These cells have the following functional regions: the outer segment, the inner segment, cell bodies and their synapic terminals. An overview of the anatomy is shown in Figure 2.

In rods, the outer segment is slender and rod shaped, and the inner segment connects to the cell body through the outer fiber. In cones, the outer segment is shorter, and has a conical tip. The inner segment is also continuous with the cell body.

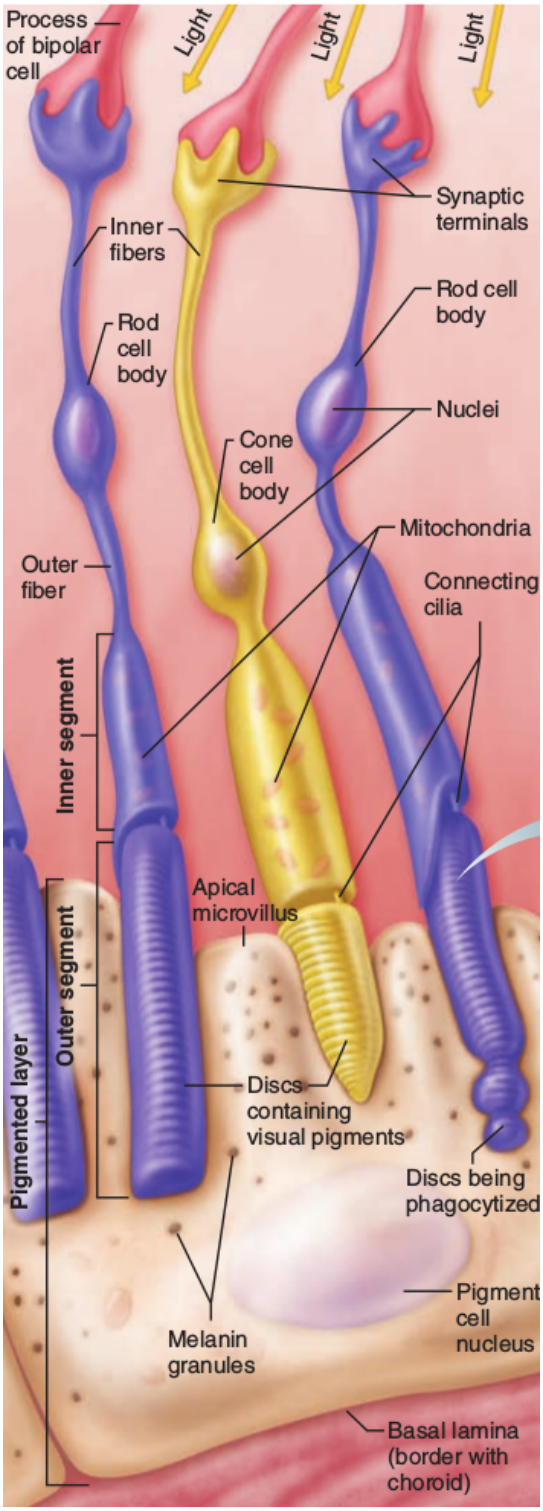

Fig. 2. The anatomy of cones and rods [1]. Picture courtesy of Electronic Publishing Services Inc.

In the outer segments, the plasma membrane is folded into discs, to increase the surface area for trapping light. Visual pigments (*photopigments*) are embedded in these discs, which change shape when they absorb any incoming light. In rods, these discs are discontinuous, and are stacked in a cylinder of plasma membrane. In cones, the discs are continuous with the

plasma membrane.

Cones are responsible for daylight vision. They have three different pigments for different light colors (wavelengths), which results in a colourful view of the world. Their sensitivity to a light stimulus is quite low, and they need bright light to be activated. The response time to a light stimulus is however fast. Cones almost have a 1 on 1 relation to bipolar cells, which in turn send the signals to ganglion cells. This means that almost each cone has its own "labeled line" to the higher visual centers. This results in a high visual acuity.

Rods are responsible for night and peripheral vision. They only have one kind of photopigment, so it is not possible to distinguish different colors with rods. Rods are highly sensitive to a light stimulus, and are completely saturated in daylight. They respond slowly to a light stimulus (in a dark room you often have to wait before your eyes have adjusted and actually can see something). Rods do not have a personal ganglion cell, and a single ganglion can have as many as 100 rods connected. The image in the higher visual centers are therefore fuzzy and indistinct.

D. Visual pathway to the CNS

The axons of the ganglion cells leave the retina at the optic disc to form the optic fiber. At the *optic chiasma* some nerve fibers cross, and some do not. The reason for this is to combine the left and right half of the visual field together. The right half of the visual field goes to the left half of the brain, and vice versa. The signal then continues in the optic tract, and most fibers end in the *lateral geniculate nuclei* of the thalamus. A few fibers from the optic tract end in the *superior colliculi*, controlling most of visual reflexes. The axons of the neurons in lateral geniculate nuclei project in turn through the *geniculocalcarine tract*, or *optic radiations* to the *primary visual cortex*. The whole pathway is illustrated in Figure 3. Note throughout the whole path, every nucleus and fiber is well structured: it is well defined what regions are responsible for what part of the visual field.

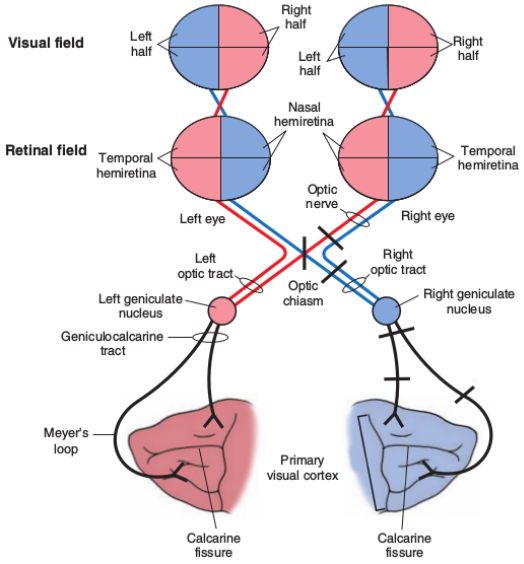

Fig. 3. The pathway from the eye to the visual cortex. Note that in the optic chiasma the left and right parts of the visual field both eyes see are combined. [2]. Picture courtesy of Siegel et al.

III. Artificial Vision

There are several possibilities to induce artificial images in a person. In this essay the following approaches are discussed: epiretinal implants, stimulation of the optic nerve and stimulation of the lateral geniculate nucleus.

A. Epiretinal implants

The idea of an epiretinal implant is an electrode array on the inside of the eye, lying on the surface of the retina, directly stimulating the retinal ganglion cells. An external camera and microprocessor is used to capture and process the image, and in turn stimulate the electrode array either by cable or wirelessly.

Advantages of an epiretinal implant include [3]:

- Bypass the retina, able to induce images even with degenerated retinal cells.
- Vitreous Humour can be used as heat sink.
- Implantable part of the device is small, visual processing etc. happens outside the body. The doctor also has full control over the image processing, and the software can be easily changed.

Of course, there are also some disadvantages [3]–[5]:

- The whole visual pathway must be intact, and epiretinal implants are therefore no option for patients with damage to for example the optic nerve or optic tract.
- Currently patients have a lot of external devices to be carried with them, but this can probably be reduced in the future with the miniaturisation of electronics.
- Stimulation of a ganglion cell can also activate nearby axons, resulting in a fuzzy image.
- Limited space available in the eye, and the device can not weigh too much because of large acceleration forces when the eye moves.
- Hard to fixate the electrode in the eye.
- In the fovea, ganglion cell bodies stack up to 5 to 7 layers deep, which may hinder the development of a prosthesis with a higher resolution in the future.

One of the most successful epiretinal implants is the Argus II, developed by Second Sight Medical Products Inc. It is the first implant to receive FDA approval and the CE mark in Europe. It consists of a 60-channel electrode array, an inductive coil to transmit power and the signal to the electrode, a camera on a pair of glasses, and a video processing unit (VPU) [6].

B. Optic nerve stimulations

The optic nerve is also a potential site for the implantation of a visual prosthesis. One group researching this possibility is the group of Veraart et al. [7]. They implanted a spiral cuff electrode on the outside surface of the optic nerve. Because of the retinotopic organization of the nerve fiber and with a multi-contact electrode and selective activation techniques, it is possible to position phosphenes in the visual field [3], [8].

A visual prosthesis at the optic nerve has definitely potential [3], [5]:

- Entire visual field is located in a small area.
- Viable location for an implant and reachable with surgery.
- Implantable part of the device is small, visual processing etc. happens outside the body. The doctor also has full control over the image processing, and the software can be easily changed.

However, there are also some disadvantages [3], [5]:

- Optic nerve is very dense: approximately 1.2 million axons in a nerve which has a diameter of 2 mm. This makes it difficult to create a precise image.
- Stimulates the optic nerve directly, and therefore lose the processing power of bipolar, horizontal and amacrine cells. This means more signal processing for the implant.
- The fibers for the central vision are in the middle of the nerve fiber, so one will always stimulate some peripheral fibers when the fibers for the central vision are stimulated.

The results with the volunteer of the study were encouraging, which could interact with the environment and recognize patterns [9].

C. Stimulation of the lateral geniculate nucleus

Stimulating the lateral geniculate nucleus is one of the more recent approaches of creating artificial phosphenes [10]. Phosphene creation is done by placing electrodes in the right areas and stimulating those areas in the lateral geniculate nucleus, where the visual field is well structured.

Advantages of stimulating the lateral geniculate nucleus include [5], [10]:

- The visual field is contained in a compact area.
- The central vision has a disproportionally large representation in lateral geniculate nucleus, which should make it easier to generate images with a high visual acuity. The structure of the lateral geniculate nucleus is also well known and characterized.
- Able to reach the lateral geniculate nucleus with the same surgical methods as used today for deep brain stimulation (for treatment of Parkinson etc.)
- Lies deep in the brain, so when electrodes are placed, the probability that the electrodes move is low.
- Can be used as treatment for a lot of causes of blindness. No need for the retina and the optic nerve.
- Implantable part of the device is small, visual processing etc. happens outside the body. The doctor also has full control over the image processing, and the software can be easily changed.

Some disadvantages of stimulating the lateral geniculate nucleus [5], [10]:

- Lies deep in the brain, so altough it is possible to reach it with the current surgical methods, compared to other visual prostheses this method has a higher risk in damaging other brain tissue.
- Behind the optic chiasma, which means each hemisphere handles one half of the visual field. For a full visual field one would need a visual prosthesis on both sides.

A visual prosthesis stimulating the lateral geniculate nucleus has great potential, but the current state is still in early stages, and there haven't been any human trials yet.

D. Other approaches

There are more approaches to creating phosphenes, for example subretinal implants or cortical implants, but these approaches will not be discussed in this document.

IV. Discussion

A. Visual prostheses in the future

The epiretinal implants are currently the most advanced visual prostheses available. One of these implants is already available world wide, with FDA approval and the CE mark. If you are blind, this would be the best choice at this moment. The company behind the Argus II [6], also says that patients with the next generation Argus will be able to perceive colour. But, the epiretinal does have several disadvantages which may be hard to overcome in the future.

For one, there are some questions whether high image resolution can be achieved using a retinal approach [5]. Also, the retina is a delicate piece of tissue, and must be handled with a lot of care, and there is a relatively high risk of damaging the tissue with surgery. This also puts significant restrictions on the properties of the device itself. Furthermore, the most common (neural) cause for blindness in developed countries is glaucoma [11], which also damages the ganglion cells, which makes it impossible to use a retinal approach.

A solution for blind people where a retinal approach is not possible, is the visual prosthesis on the optic nerve or the lateral geniculate nucleus. Of these two options, I think the lateral geniculate nucleus option is the best, and has the most potential. While the optic nerve visual prosthesis has already been tested on humans, it does have more disadvantages than the lateral geniculate nucleus approach.

I even think that a visual prosthesis stimulating the lateral geniculate nucleus has the most potential of all. The surface area available for stimulations is relatively large, while the whole visual field is still represented in a compact area. The structure of the lateral geniculate nucleus is well known, and it will only become better with better brain scanning and monitoring equipment. Plus, it is reachable with current surgical methods.

But, no matter the location of the visual prosthesis, there are other obstacles to overcome before we can really reach a high visual acuity. The size of the electrodes needs to shrink a lot, up to a few micrometers, while still being biocompatible, able to control the amount of charge, and more [12].

Next, there is the problem of power consumption and transmission. Biological media has a relatively large resistance, demanding more power from the current driver.

Other research that could help increase the visual acuity of prostheses downstream of the retina is to find out which locations of phosphenes result in the highest visual acuity [5], [13].

Altogether, every visual prosthesis will benefit from the continuous effort to miniaturise electronics, lower power consumption, and more efficient methods for wireless power transfer.

B. Other applications

The knowledge of our visual system is not only applicable to blind patients. The visual system is electrically stimulated, but the system that generates the stimulus can use anything as a source. One can dream about the possibilities for people with healthy vision:

- Why limit to visible light? It could be possible to also show infrared sources on the visual field. This could be useful for the military and police, who can then see if there are any people inside a building or a room.
- It would be very useful if it was possible to add custom graphics to our visual field, a sort of Google Glass, but then integrated in our visual field.
- If it is possible to decode the signal anywhere in the optic pathway, it would be possible to create some sort of recoding device.

And possibly in the future, it is possible to integrate all the required electronics in a custom eye ball. Maybe even a camera with zoom function!

When keeping these possibilities in mind, retinal visual prostheses have another disadvantage: epiretinal implants place an electrode array on the inside of the eye. This is of course not really convenient for people with healthy vision, where an electrode array would sit in front of their photoreceptor cells. While using a visual prosthesis downstream of the retina, this is not a problem, although mixing an artificial signal with the natural one may not be that trivial.

V. Conclusion

The last few years there has been a tremendous progression in visual prostheses. There is an epiretinal implant with FDA approval and CE mark, which can already restore sight to blind people in a limited way. With smaller and smaller electronics the visual acuity will continue to rise.

Another promising solution is a visual prosthesis which stimulates the lateral geniculate nucleus. It is probably easier to achieve high resolution images with the lateral geniculate nucleus than with an epiretinal implant. But this device has not had any human trials yet, and it is not yet as advanced as the current epiretinal solutions.

Research for visual prostheses can have a huge impact on the future, because a lot of knowledge can also be used to think of applications for people with healthy vision, and with the increasing rate of technological progression, it may not even take that long.

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