

Trends and Challenges of BCI-based Visual Prostheses

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Abstract. The development of visual prostheses is a popular field of research in recent years. Several approaches had been suggested to create artificial vision, with varying progress to success. This work attempts to briefly review the current state of research and its implication on patients. We mainly focus on the novel retinal and cortical visual prostheses, and investigate effect of various stimulation regions. Eventually, we also presented our concerns and challenges about this field.

Keywords: Visual Prostheses, Brain Computer Interface.

1. Introduction

As of 2020, an estimated population of 49.1 million worldwide is affected by blindness, with an additional 33.6 million affected by severe visual impairments [1]. Despite investments to improve eye health in the global population, the blind population shows an alarming increase in number in comparison to the 36 million estimated in 2017 [2]. This can be partially attributed to the change in demographics. The world population continues increasing, and a longer global life expectancy leads to a larger proportion of elders, which makes up most of the blind population [3].

With such developments, providing appropriate assistance for the blind becomes an ever more pressing matter. Many devices are being developed to assist them in their daily life, invasive brain-computer interfaces called visual prostheses being one of the methods used. Though sensory substitution devices are considered safer with no requirements of surgery, many of them have high cognitive demands, which makes them less suitable for the older population to use. The visual prostheses, on the other hand, utilizes what remains of the visual pathway to partially restore the user's vision, with no requirements for the user to interpret alternative sensory. Often, a camera is used to pick up visual images, then the image is translated into electrical stimulations which is given off by implanted microelectrode arrays. Unlike natural vision, the electric current given off by those devices only enable users to see white light spots called phosphenes. Changing the position and strength of stimulation causes shifts the brightness, position, and size of phosphenes, enabling the devices to conjure up a black-and-white, low-resolution image.

Depending on which part of the visual pathway is damaged, various regions can act as an implant site, ranging from the neural retina to the visual cortex. Research proved many implant sites to be effective, but due to technical challenges, some products are more accessible than others. As a newly developed technique, there is considerable risk involved with the surgical processes, and relatively low guarantee for proper function.

2. Retinal prostheses

Of all the attempts to restore vision with invasive BCIs, retinal prostheses are the only devices with a technology mature enough for regulatory approval. These devices were widely tested on patients with retinis pigmentosa (RP), with which the patients gradually lose the photoreceptor cells in the neural retina but have otherwise intact visual pathways. Though other methods of treatment such as gene therapy and stem cell therapy show potential in laboratories, research on those methods is still in the earlier phases.

Retinal prostheses have implants replace the role of photoreceptors, using electric stimulations instead of light to create a vision. The retina needs to be mostly intact for the use of retinal prostheses, as the formation of phosphenes rely heavily on functional ganglion cells. This requires patients to

have past functional vision for the implantation of the devices, and an additional screening for residual function is required before the implantation. The arrays can be implanted on the surface of (epiretinal), in between (subretinal) the neural retina, or between the sclera and choroid (suprachoroidal). The epiretinal approach was the first to be approved, and has the lowest surgical risk due to good accessibility and use of previously existing vitrectomy techniques. Meanwhile, the subretinal implants have the highest potential for reaching higher resolution with an additional risk due to its more unusual surgical procedures. Suprachoroidal implants is located the furthest from the neural retina. While this guarantees least disturbance of the remaining neural tissue, a higher voltage threshold must be met to generate a phosphene, making the users more prone to electrical damages. The following are some examples of those approaches.

2.1. Epiretinal

The earliest approved retinal protheses, Argus II™, is implanted exclusively in RP patients over 25 years old, with no or bare light perception and a history of functional vision. It consists of a camera attached to a pair of glasses, a video processing unit (VPU) which translates the image to electrical stimulation, the glasses that relays the signal from the VPU to the implant coil, a cable between the implant coil and the electrode array, and a 6×10 platinum electrode array implanted at the fovea. The device provides a visual angle of 20° [4].

2.2. Subretinal

Instead of processing video input, Alpha AMS™ uses stimulation units in a process more akin to photoreceptors. Each unit includes a photodiode, an amplifier, and an electrode, enabling the unit to give off an electric stimulus when light is present. The silicon chip can have as many as 1600 units, allowing for much more detailed image. The visual angle between two neighbouring pixels is estimated to be around 0.233° , adding up to about 10° overall [5]. This type of approach is also used in other research groups in hope of developing cableless retinal protheses. One such example is the Okayama University-type retinal prosthesis (OUReP), which relies on photoelectric dyes on a polyethyl film to give off electric stimulation when light is received [6].

2.3. Suprachoroidal

The Bionic Vision Australia research group is dedicated to the production of a suprachoroidal protheses. Two generations of protheses were produced, with the second generation entering clinical trial in 2021. The composition of the protheses is quite similar with the epiretinal approach, including the camera, video processing, microelectrode array, and a cable that leads to the implant. Though it only consists of 44 electrode units, it provides a larger visual angle of $37.6 \times 27.6^\circ$ [7].

2.4. Overall evaluation

Despite many attempts and successes, the patients' experience with retinal protheses is surprisingly neutral. Besides low resolution, the reason also comes down to the narrow visual field provided by the devices, which can render the users' ability to navigate and recognize objects. While the constructed vision allows users to perform many visual tasks, smooth navigation in daily life requires a visual angle of at least 30° , which is not provided by any commercial protheses so far. Users would need to do a sweeping motion to gain enough information of their surroundings, and the lack of more input can be a frustrating experience. The challenge that a larger angle poses comes from the surgical risks, which increases with the diameter of the implant. A larger incision must be made for its insertion, and the implant must be specifically shaped to better adhere to the curvature of the eye.

3. Cortical prostheses

Located on the other end of the visual pathway, the visual cortex is more accessible by surgical methods than other “midstream” neurons, making it an intensively researched region for vision recovery. There are currently five research groups at least dedicated specifically to developing visual cortical prostheses, and many more ongoing researches may contribute to this subject. With previous success in restoring hearing via similar approach, this field of research proves to be very promising.

The correspondence between cortical stimulation and the perception of phosphenes is mostly established on data collected from patients, either injured or undergoing surgery. Due to the large surface area of the cortex, cortical prostheses allow for multiple electrode arrays to be implanted. This gives the potential of perceiving visual input of much higher quality. Stimulation at the end of the visual pathway also applies to all users with functional occipital lobes, making its target users much less specified. Since the surgical process directly involves the brain, potential users need to be evaluated in many more dimensions to reduce the risk, including physical and psychological health as well as responses to cortical stimulation.

Despite previous observations on cortical stimulation, the mapping of electric stimulation to phosphenes is still required for every individual, especially since the mapping of the cortex will change after a period of absence of visual input in the process of cross-modal adaptation [8]. This is a common challenge in other cortical prostheses as well. One method to evaluate the state of the visual cortex as well as mapping is via the use of transcranial magnetic stimulation (TMS). By generating a rapidly changing magnetic field that penetrates the skull, it is possible to induce an ionic current at a particular site without physically inserting an electrode.

So far, research on cortical prostheses shows steady progress. With the Gennaris bionic vision system entering the phases of human clinical trials [9], it seems to be a matter of time before this approach produces a regulatory approved product.

4. Stimulation of other regions

Other implantation sites are harder to reach, and hence not as thoroughly researched as the retina or the visual cortex. Still, they provide alternatives in the rare case when neither previous approach is applicable, and some have unique qualities that may give rise to more qualified vision.

4.1. Optic nerve

Stimulation of the optic nerve experience challenges similar with retinal prostheses, in terms that the implantation site is small and users can only perceive a narrow visual field, but has a slightly wider range of target population since intact ganglion cells in retina are not required.

Despite proof that phosphenes generated by stimulating the optic nerve can assist in pattern recognition [10], due to its limitations, research in this approach seems to dwindle in the past twenty years.

4.2. Lateral geniculate nucleus

The LGN is unique in the way pathways specific for colour and motion detection are physically separated. Though its overall area cannot be compared to the visual cortex, the majority of the region is responsible for the process of the central 15° of the visual field [11], allowing the electrode to be implanted more sparsely to reduce possible damage. While stimulation of LGN is historically reported to generate complex visual phenomena, it is shown that micro-stimulation enables discrete visual perception [12], making it another potential candidate for prosthetic implantation.

5. Conclusions

In this paper, a comprehensive review of BCI-based visual prostheses is presented. There are still several challenges and concerns as follows. One challenge shared by all visual prostheses is the low

quality of the induced vision. The perceived images have low resolution, narrow angle of vision, and lack colour. While retinal prostheses have the potential to become “cellular level”, it is far from natural vision. So far, the generation of colour remains an unsolved challenge in the field of visual prostheses. The answer may lie in LGN or cortical prostheses.

Implanted devices are bound to deteriorate over time. This requires for rapid assessments when they show failure, and safe surgical methods to repeat the process for multiple times. This already proves to be a serious issue for the users of Argus II; some of the devices had failed in the past few years, and the implant becomes a nuisance as maintenance is no longer provided by the bankrupt company [13]. Meanwhile, attempts are still being made to make the devices safer and more durable.

In comparison to visual prostheses, sensory substitution devices are much safer and more accessible. Further research is required to lower the price and improve their performances for visual prostheses to become a reliable substitution for other tools.

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