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Brain machine interfaces – sensors and implementations case study : ***Neuralink*** [1]

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Contents

1 Introduction

Recent advancements in information and computation technologies have brought us closer and closer to computers, making them the machines we interact with the most and turning them into essential items, not only in our everyday life, but also in professional applications. So far, our interactions with computers have always been done using input/output devices such as screens, keyboards, mice, etc. To that extent, the logical next step is to get rid of the interface device itself, and move towards systems that can be directly controlled with our brains, creating an almost symbiotic relationship between human and machine.

A "brain-computer interface", "brain-machine interface" or sometimes also called "neural - control interface" , (abbreviated as BCI, BMI or NCI respectively and used interchangeably in this paper) are the solution to that query. Such devices represent a method of direct, ideally bi-directional, communication between an external device, such as a computer, and a brain. Brain-computer interfaces are therefore capable of acquiring signals originated from the axon potentials firing in the brain. BMI systems need to analyze these signals, and translate them into commands to be carried out by external devices. The high precision in signal analysis needed to perform such actions also require the host's brain to be modified, or augmented, in order to implant the necessary elements for data acquisition from the brain neurons themselves.

Applications of BCIs are mostly aimed at the medical sector : "The main goal of BCI is to replace or restore useful function to people disabled by neuromuscular disorders such as amyotrophic lateral sclerosis, cerebral palsy, stroke, or spinal cord injury." [2]. Using the natural plasticity of the brain, BCIs can for example be used to provide the specific signals required to help in the recovering of victims of physical trauma. With more research, this technology could be applied to help people with impaired mental or physical abilities,or even cause relief to some mental illness. Naturally, as patients become more familiar with the technology, it's effectiveness will increase : "The user, often after a period of training, generates brain signals that encode intention, and the BCI, also after training, decodes the signals and translates them into commands to an output device that accomplishes the user's intention." [2]. The importance in developing this technology thus stems from the fact that, in it's very nature, it has an extremely wide range of applications, and a very promising future in the aforementioned fields.

As with any emerging technology, BCI faces many setbacks : in the methods used to record the necessary brain signals, in the mass-manufacturability of BCI systems, or their public acceptance.

In this paper we will therefore present the possible solutions offered by the Neuralink system [1], compare it with current mainstream BCI technologies, and find possible solutions for the future of BCIs.

2 A presentation of Neuralink's BMI

One of the main problems holding back the development, mass-production and wide adoption in the clinical sector is the low channel count of present day BMIs which then limits the bandwidth of communication between brain and machine. As stated by researchers from the *Berlin brain-computer interface* : "BCI users can perceive a high rate of information transfer from the display, but have a low-bandwidth communication in their control actions." [3]. This essentially means that even though a human brain can easily process a lot of external information (for example, information communicated by the computer using a display), the bi-directional communication is limited by the link between the brain itself and the computer, creating a bottleneck in the flow of control actions issued by the brain.

Neuralink's focus is thus to find a viable solution to this problem by developing a high-bandwidth BMI system, capable of recording a high number of neurons, that can be implemented at a high scale in the medical field, reduce costs, and increase adoption of such systems.

Neuralink's goal is to be able to record device on a clinical device that a user can take home and use on their own with orders of magnitude more channels, orders of magnitude more neurons that are being recorded and with that people will be able to acquire naturalistic control of a computer not just with the mouse but the keyboard and potentially other devices.

The goal is for this communication to be bidirectional. The idea that information could be signaled into the brain seem fantastical that you could write information to the brain. However, the building blocks to create this technology already exist. If we pass a small amount of current through the electrode the user is able to stimulate the axon potential of one or several cells. This has already been done to recover hearing to the deaf and most recently to restore vision to the blind in a more rudimentary way.

What Neural link would like to do is to have small enough electrodes that are small enough and of high enough density that they can tap into the rich collection of maps to recreate a vivid image to the blind. This could be just another example of how this example could be used.

2.1 Biomedical discussion : brain signals

When studying and analyzing brain functionalities, precise measurements of brain activities at different scales must be performed. These range from non invasive imaging modalities measuring the brains electrical activity such as electroencephalography (EEG), to the invasive and more precise methods that we will discuss.

EEG intends to measure changes in voltage between electrode pairs placed on the patient's scalp, which result from ionic currents between neurons in the brain ; the resulting waveforms are called brain waves. [4] This method is very practical since the electrode pairs can be mass manufactured into ready-to-use EEG caps, that standardize the practice and improve ease of use. However, despite having an *acceptable* temporal resolution (ie. between 10 ms to 100 ms) [5], EEG lacks from spatial resolution on the scalp and requires further interpretation of the resulting waveforms in order to interpolate which areas of the brain are being active at any given moment. [6] To implement a BMI, higher spatial resolution and improve temporal resolution must be achieved.

Different methods and their characteristic temporal and spatial resolutions are shown below, where Neuralink lies in the "Extracellular Action Potentials from Single Neurons" category, thus providing high tempospatial resolution :

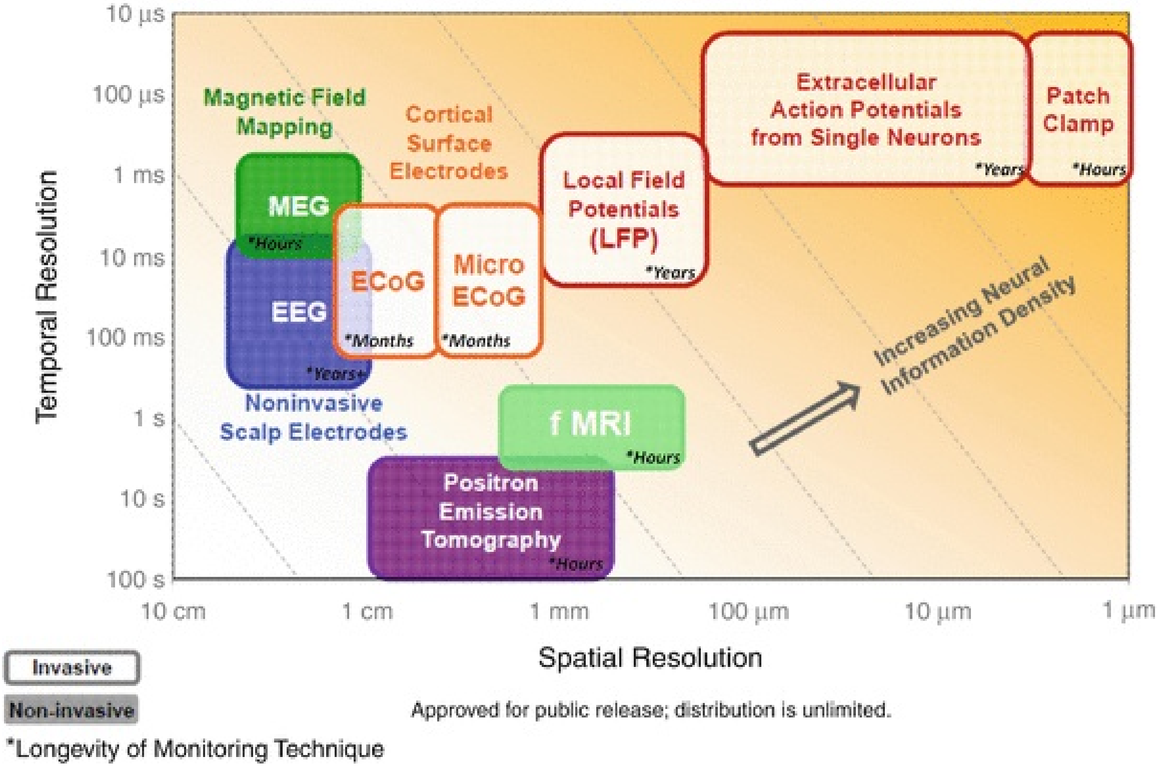

Figure 1: Spatio-temporal resolution of current brain monitoring technologies.

The method implemented in current BMIs and therefore the method used by Neuralink is to record the brain's electrical activity directly from the neurons. This can be either by recording the field potentials from a group of neurons, or by recording extracellular action potentials from a single neuron or a small group (can also record chemical activity in the synapses). In general it is preferred to record electrical activity from a single neuron. [5] Neuralink's approach is in that sense fairly standard, as they chose to record single neuron electrophysiological and extramolecular signals in the preliminary tests of the system, meaning that the system records extramolecular electric voltage fluctuations of a single neuron. [1]

A sample of the recorded signals by a Neuralink prototype can be seen below, with 32 waveforms, each corresponding to a different neural probe connected to a single inserted thread :

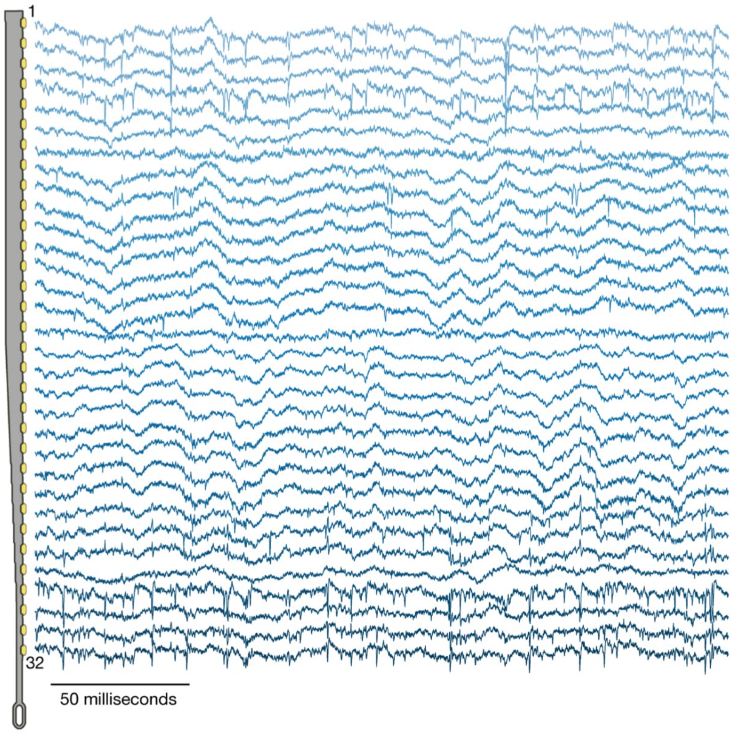

Figure 2: Unfiltered neural signals acquired in a rat cerebral cortex by a 32 channel neural thread. [1]

Spikes are clearly visible, which in turn will aid in the signal analysis and decoding.

2.2 Neuralink's approach to integrated neural probes

A fundamental aspect, and also one of the greatest challenges, in BMIs is the creation of the neural probes themselves. Despite most using biocompatibles microelectrodes, considered a standard in this area of applications [1], the design of the neural probes *hosting the electrodes* is to be considered.

2.2.1 Gold plated microelectrodes

A BMI is intended for long term implanting and recording, by its very nature, as seen in fig. 1. Therefore the design of the neural probes needs to be such that it ensures high biocompatibility, safety, and longevity. In the long term, the neural probes would also need to be able to integrate high-density, low power electronics to facilitate wireless operation of the BMI, something which is currently not possible without using an external module for data transfer. [1]

Currently, long-term devices for neural recording and BMI application use rigid metals and semiconductors for their construction. [1] [7] [8] These methods have a clear advantage : the insertion of such probes into the cerebral tissues and penetration of such tissues is rendered easier, mostly because of said rigidness. However inserting foreign objects into the brain, that vastly differ from their surrounding medium in size, Young modulus, and bending stiffness may push the body into immune responses against the probes, which in turn hinder their longevity and functionality. Besides, the fixed geometry of rigid probes limit the sites where they can be inserted without disturbing the cardiovascular system, and thus limit the number of neurons that can be recorded. [1] [9]

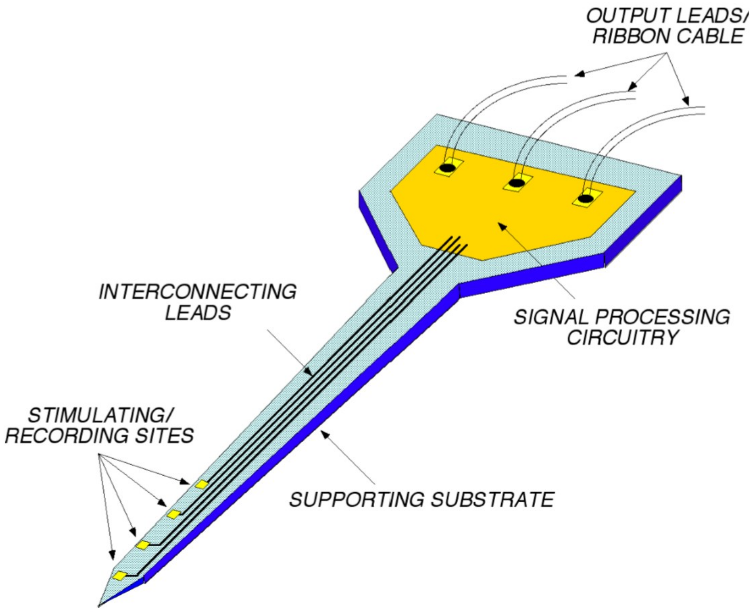

Figure 3: Basic representation of a multi-electrode neural probe. Equivalent to Neuralink. [8]

A logical solution to this problem is to use flexible neural probes, with multiple electrodes per probe, which improve biocompatibility at the expenses of ease of insertion. [2]

Neuralink has thus developed a thread that intends to be biocompatible, not only in the materials used but also in the dimensions [3] while keeping recording channel count high. As mentionned, they use a multiple-electrode thread (current models incorporate 32 electrodes per thread), whose metal film is created by thin film lithography techniques, and using biocompatible materials for the fabrication of the main substrate and dielectric such as polymide. [1] This allows for increased flexibility in the dimensions attainable, and threads

[1] fig. 2 : current BMIs from Neuralink must use a wired interface

[2] The insertion of such probes into the neural cortex will be discussed in section 2.3

[3] A thread with a bigger size than the surrounding medium of insertion can lead to neural displacement of tissues or even vascular damage. [1]

can range from 5 to 50 um in width, 4 to 6 um in thickness and up to 20 um in length. These threads are then combined into arrays of 48 or 96 threads, which are finally connected to an electronic interface that handles data acquisition and signal amplification for further transfer to the handling computer. [1]

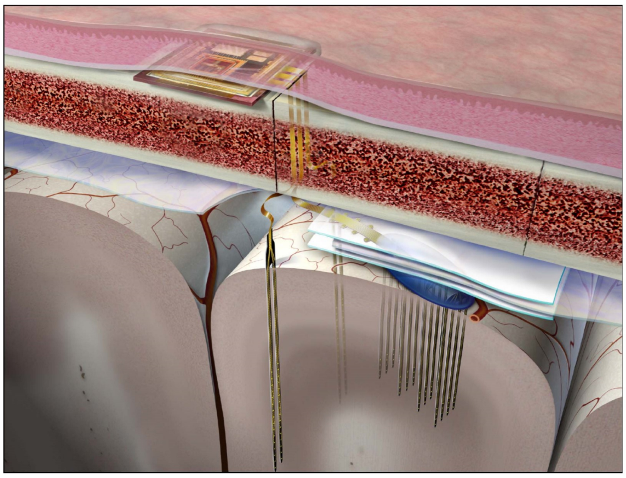

Figure 4: 3D render of a BMI equivalent to Neuralink's proposal inserted into the cerebral cortex. [8]

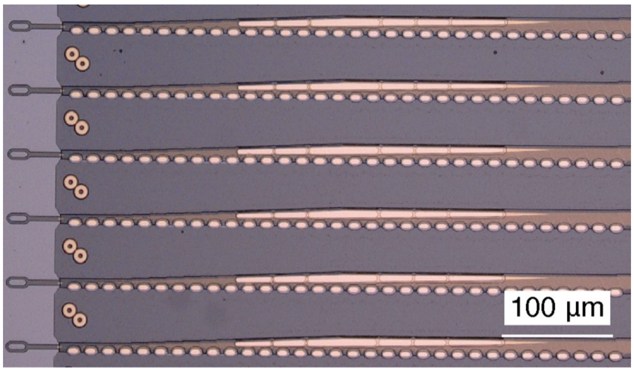

Figure 5: Example 1 of a Neuralink multi-electrode thread. [1]

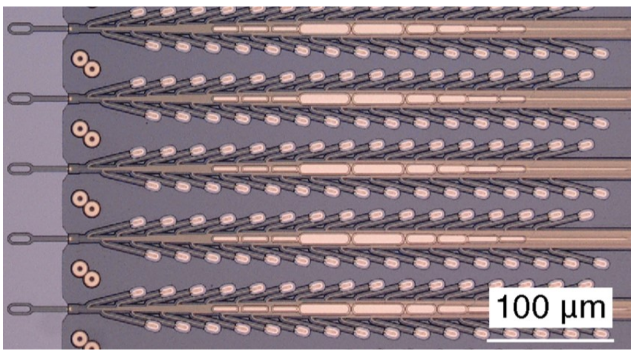

Figure 6: Example 2 of a Neuralink multi-electrode thread. [1]

The electrodes (acquisition sites) handling the raw data acquisition are gold electrodes with a small surface area : they are usually in the range of 10x20 um. Thus to improve the charge carrying capacity of the data acquisition site (a relevant improvement for data acquisition using electrophysiology), the electrodes undergo surface modifications. Two examples of the used treatements are electrically conductive polymer poly-ethylenedioxythiophene doped with polystyrene sulfonate (PEDOT:PSS) and iridium oxide (IrOx), achieving impedances of 36,97±4,68kΩ (n = 257 electrodes) and 56,46±7,10kΩ (n = 588) for PEDOT:PSS and IrOx, respectively. Further research to insure the biocompatibility of these gold electrodes remains to be conclusive. [1]

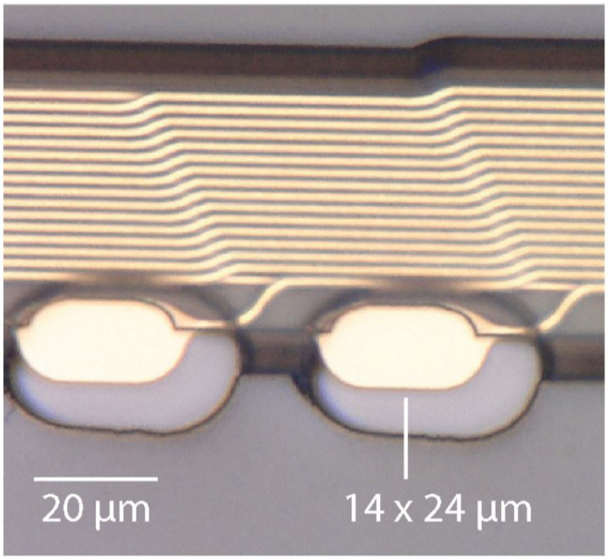

Figure 7: Detailed picture of a gold plated electrode. [1]

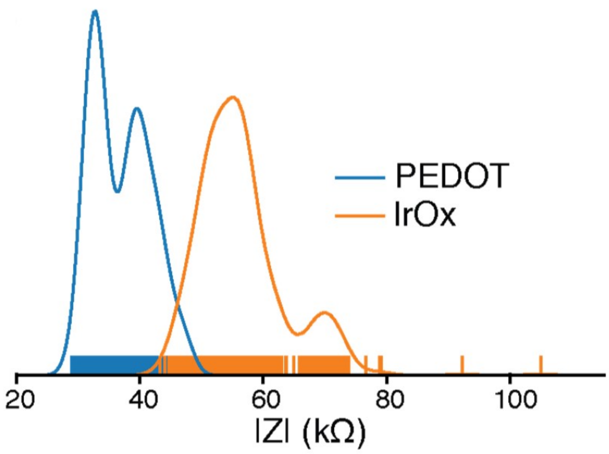

Figure 8: Impedance distribution of a gold plated electrode [1]

2.3 Implanting electrodes

As mentioned previously, a common approach in the developpement of more recent neural electrode probes is the use of thin film polymers in their fabrication process, leading to better biocompatibility, but limiting their insertion capabilities into the brain. The question then arises as to how can one insert such flexible neural probes into the brain in a time and cost efficient manner. Neuralink's approach is to develop a robotic system that is capable of reliable and rapid insertion of probes without damaging the cardiovascular system [10] and capable of inserting probes in scattered parts of the brain. The robot uses an insertion system comprising a needle, and a pincher, both contained within a swappable "cartridge" for ease of replacement. The needle insertion is accurate to 10 um, and has a range of travel of 400x400x150 mm with 3 degrees of freedom (DOF).

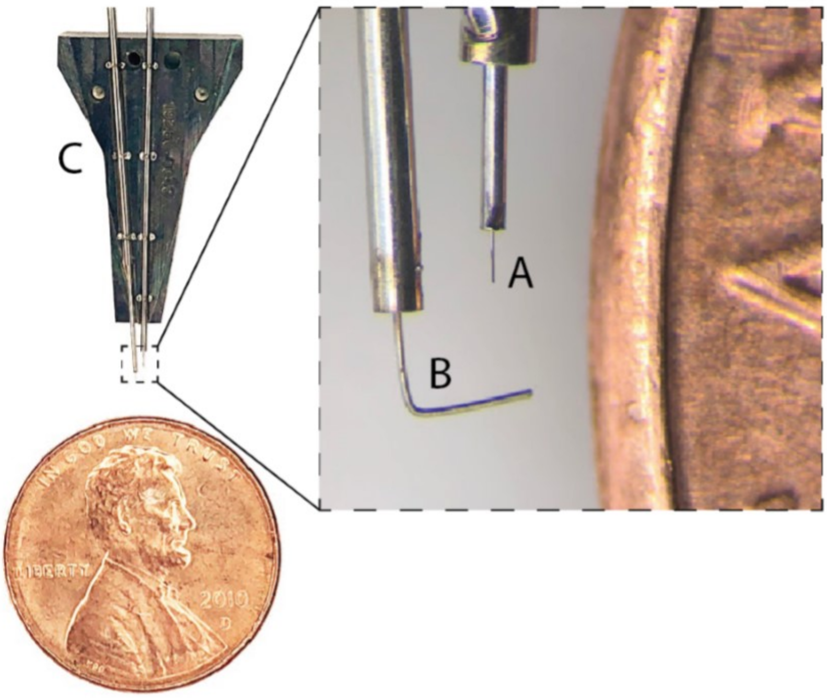

Figure 9: Needle and pincher assembly (cartridge) with a US penny for size comparison [1]

The needle is designed in the form of a hook to aid with the insertion in the brain and is driven by a linear motor with a very high retraction acceleration (up to $30'000\ mm \cdot s^{-2}$) and variable insertion speeds which in turn helps promoting the separation of the needle and the insterted probe. [1]

To guide the needle, the Neuralink team has developed an imaging stack to which the needle assembly cartridge is attached and is used for insertion targeting, live viewing of the insertion process which allows for on site verification of the performance of the robot. This assembly also includes independent 405 nm, 525 nm, 650 nm light sources that respectively : excites fluorescence in the polymide neural probe and helps localisation of the thread, estimates the location of the cortex surface, and illuminates the needle itself. Using the data gathered by the imaging stack, the robot is also capable of registering the insertion sites using structures on the skull as reference. This can then be extrapolated to select custom insertion points, create multiple paths for optimization of the insertion process, pre-select the insertion sites etc. In turn the robot then uses this information to auto-insert up to 6 threads per minute in a fully autonomous mode, with supervision from a surgeon. [1]

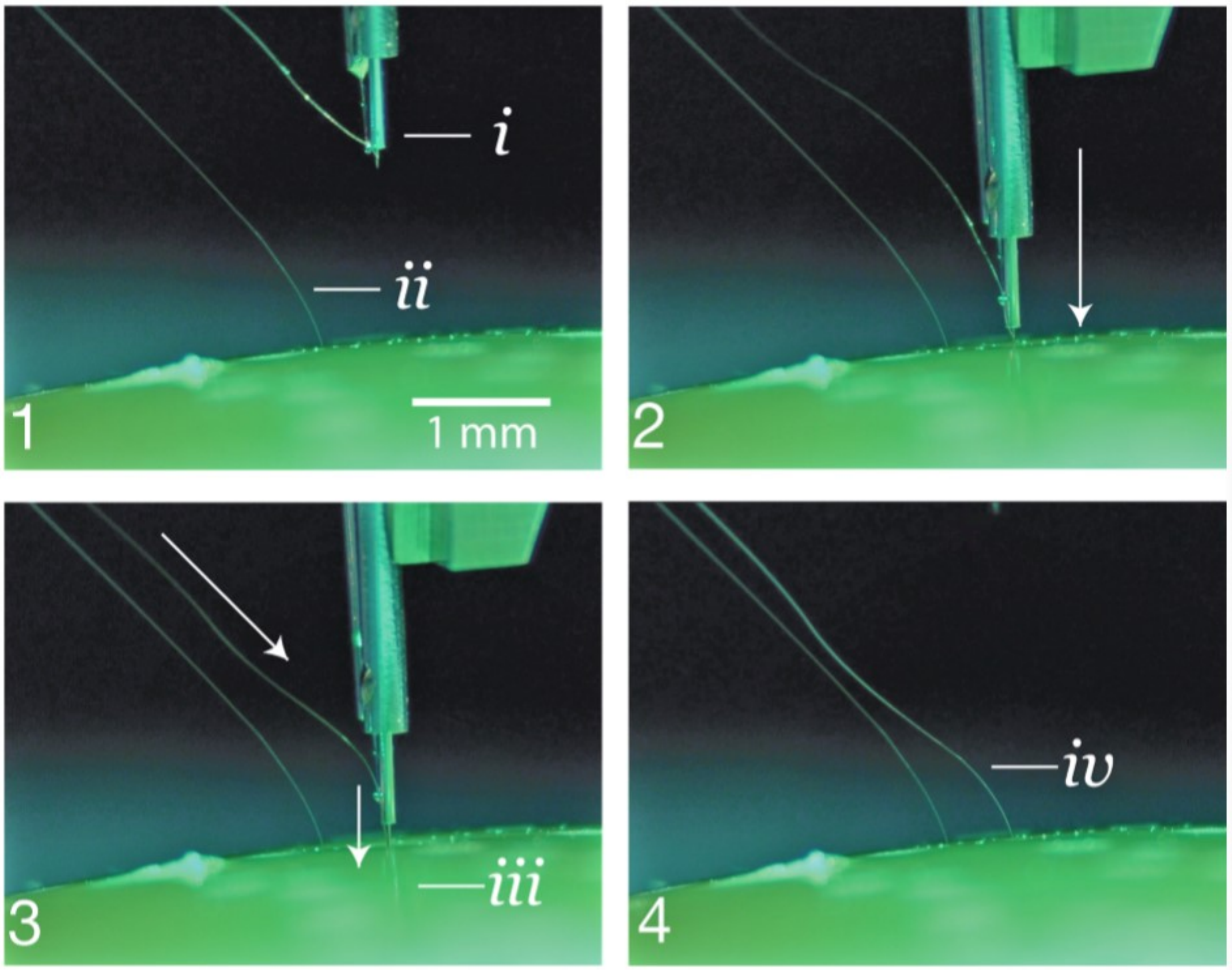

Figure 10: Insertion process of a neural probe : **1.** Initial state. *i.* needle. *ii.* previous thread. **2.** Insertion needle touches down on the brain. **3.** Needle penetrates brain up to desired depth. *iii.* inserting head **4.** Inserter pulls away. *iv.* inserted thread. [1]

Neuralink's research and improvement on this insertion technique has lead to succes rates of 87.1±12.6 % on average over 19 surgeries. However, manual correction and adjustments were needed to avoid the vascular system, which unfortunately slows down the process. Average time for the entire process is around 45 minutes, yielding an insertion rate of about 30 electrodes per minute. Robotic insertion of such flexible polymer electrodes is proving to be an effective and scalable method of inserting the sufficient elements for a high capacity BMI. [1] [10]

2.4 Developing custom electronics for BMI implementation

The last fundamental aspect in the development of a high bandwidth BMi that we will touch upon, is the set of electronic elements needed for signal analysis, recording etc.

The main challenges when developing such electronics are package size, signal amplification and power consumption. A recodring element must amplify a very small neural signal, of around 10 uV, while rejecting noise, digitizing the amplified signals and streaming them to a central processing unit, while minimizing package size and power comsumption.

Neuralink has developed an application specific integrated circuit (ASIC), comprising 256 individually addressable and programmable amplifiers, integrated ADCs, and an integrated control circuitry for management of a serial digital data output.

Number of Channels	256
Gain	42.9–59.4 dB
Bandwidth	3 Hz–27 kHz
Input-referred noise (3Hz - 10KHz)	5.9 μV_{RMS}
Maximum Differential Input Range	7.2 mV_{pp}
ADC resolution	10 bit
Analog Pixel Power	5.2 μW

Figure 11: Neuralink ASIC performance and data [1]

This circuitry has the advantage of being designed to be a part of a package that can be easily produced and replaced : a number of ASICs (the number depends on the implementation and the number of channels to be recorded) can be integrated onto a standard PCB, and form a system consisting of an FPGA controller, as well as an array of sensors (temperature, acceleremeter, etc.) and a single USB-C connector for general full badwith I/O of the processed signals towards an external computer. A system can then be housed in a moisture-proof titanium casing forming a self-contained package.

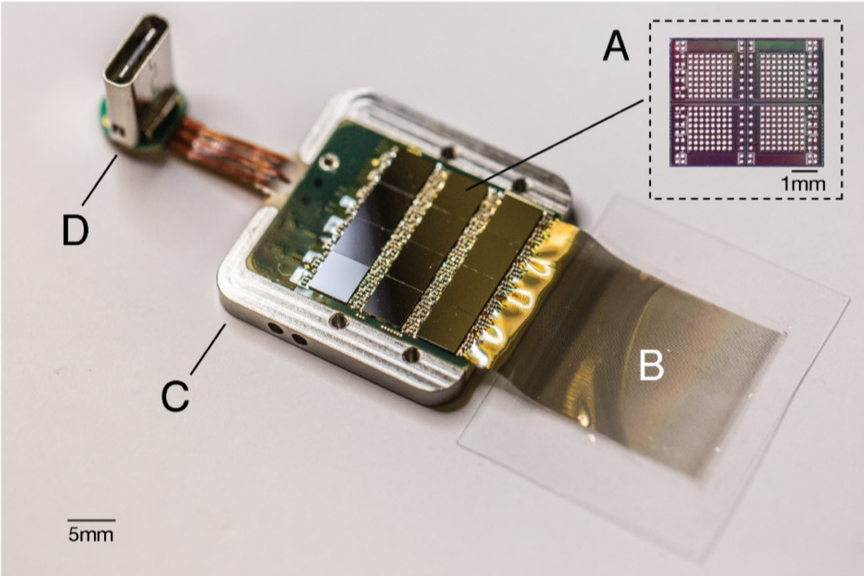

Figure 12: Neuralink packaged sensor components and ASIC. A. ASIC. B. Waterproofing elements. C. Titanium casing. D. USB-C interface. [1]

Figure 13: A application of the described system, implanted on a live rat. [1]

Neuralink has investigated several methods in data acquisition : improving bandwidth but limiting the manufacturing rate, or facilitating manufacturing at the expense of data acquisition capabilities, both systems showing promising results and low power consumption (750 mW and 550 mW respectively).

The logical following steps for BMI electronic development would be insuring interoperability, the creation of a plug and play system, and of course, a wireless BMI. fig. 14 represents the block diagram of a completely wireless and implantable system that could be used for neuroscience research or neuroprosthetis applications.

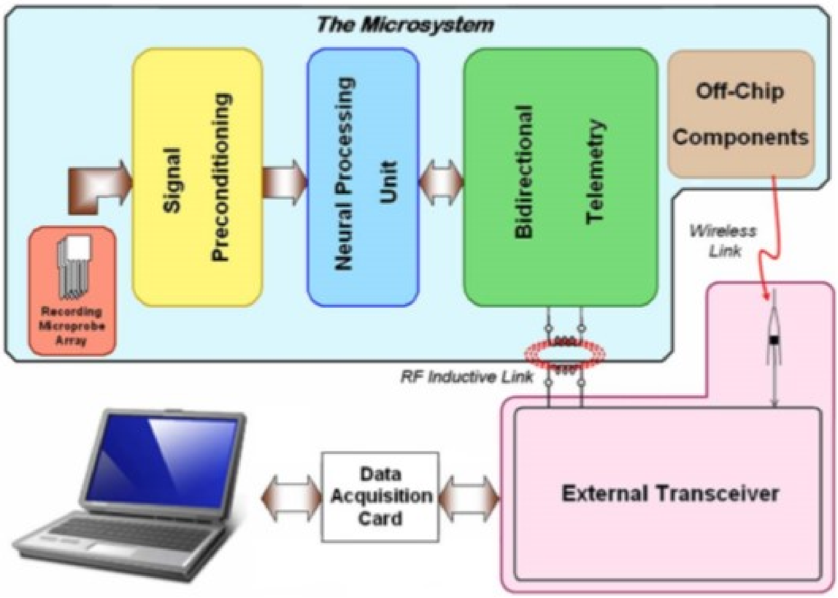

Figure 14: Block diagram of a wireless BMI [8]

3 Detecting Brain Signals

There are around 100 billion neurons working together the vast network known as the human brain. When recording brain activity we typically narrow our target to an area known as the cerebral cortex. The cerebral cortex constitutes the outer most layer of the brain. It contains between 15-20 billion neurons. With so many neurons, several different devices have been made to sample and tract neural activity in the brain. All these devices can be ranked into three categories, scale, resolution, and invasiveness. Scale is the ability for the device to cover activity across the brain. Resolution can be divided into two categories spatial and temporal. Spatial resolution is the ability of the device to distinguish activity between two different firing neurons. Temporal resolution is the ability for the device to determine when and after how much delay a neuron has been triggered. Lastly invasiveness covers how intrusive to the body the signal recording procedure is.

3.1 An invasive method vs a non invasive method

The ideal BMI interface is highly responsive with high temporal and spatial resolution whilst being minimally invasive. In this section we explore other solutions for implanting electrodes into the brain cortex and how these affect the design of the electrodes themselves. Which solution provides the best compromise between invasiveness, scale, spatial and temporal resolution. So far no neurological probe has been able to exceed in all of these categories. For this the end use of the BMI must be clearly understood as the type, number, and strength of signals vary with each different approach.

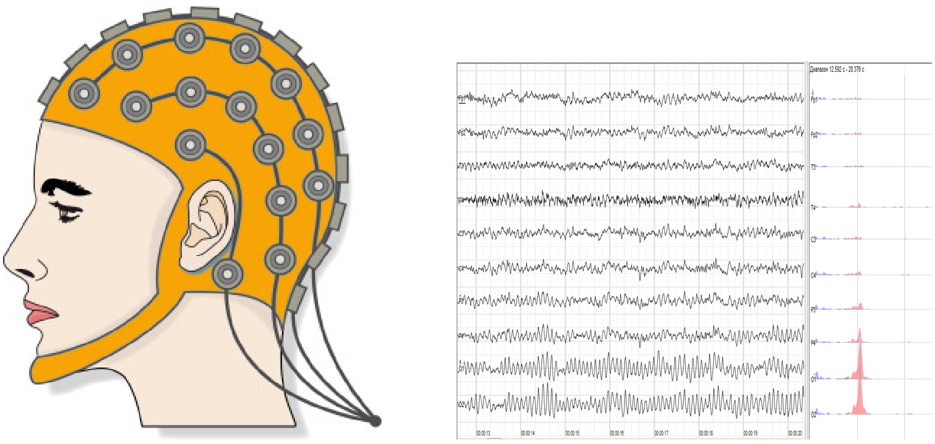

Figure 15: EEG electro-encephalography cap

One of the oldest and most widely used devices to record brain activity is the EEG (electroencephalography). An EEG places a grid of electrodes on the human scalp. The electrodes measure very small voltage fluctuations that can be mapped to brain activity within the cortical areas. This is done with a temporal resolution of about 10 ms to 100 ms. This device is one of the only devices that can be coupled to BMIs that is completely non-invasive. This device can scale through the entire scalp noninvasively with high temporal resolution. The only draw back it that is has poor spatial resolution.

An alternative that enables a higher spatial resolution is the ECoG (electrocorticography). ECoG also uses electrodes to record small fluctuations of voltage except the electrodes are placed between the skull and the epidural layer. Since an incision in the patients head must be made to place the electrodes this is a highly invasive procedure. Since there is no interference of the skull blurring out the fluctuations in voltage, ECoG has a better spatial (1cm) and temporal resolution (5 milliseconds) compared to the EEG [11].

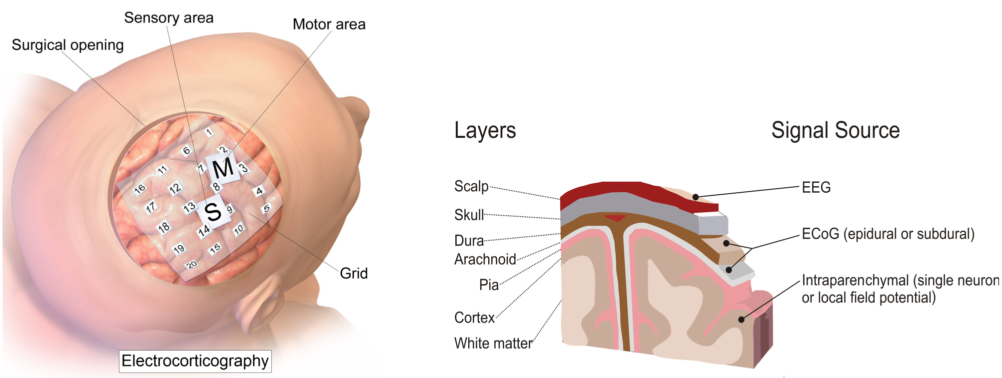

Figure 16: ECoG (electrocorticography) electrodes placements

Perhaps the most invasive tools used for BMI are LFP (local field potentials). These are no longer surface electrodes but rather microelectrode needles like the one shown in figure 17 . New techniques in manufacturing silicon wafers have allowed the fabrication of an electrode needle with a thickness 20-100 micrometers [7]. The LFP shown in 17 was produced by Dick Norman at the University of Utah. LFP works by taking a microelectrode needle and placing it one or two millimeters into the cortex. These microelectrodes offer even better temporal and spatial resolutions. In comparison to an EEG these probes are do not offer any scale of their readings. These small probes can only detect action potential inside a given radius typically of a few neurons. These electrodes however are unaware as to what is happening to the rest of the brain. Typically these electrodes are implanted into the motor cortex and are used to restore basic motor functions to a patient. They can be fabricated under precise control in a variety of patterns and shapes. These implants however are highly invasive and can carry risks like cell death. This happens on a microlevel as capillary beds are mechanically detached by the probe during insertion.

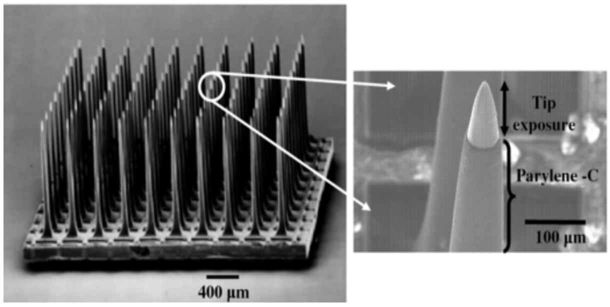

Figure 17: LFP (local field potential) microelectrode needle array

3.1.1 Electrochemically compatible neural probes

Another aspect that has seen recent progress, is the chemical aspect of the electrochemical nervous system. The main objective is to develop a set of neural probes, that in addition to being able to communicate bidirectionally with the brain, also integrate a full array of microfluidic components : valves, pumps, drug delivery channels, etc. In addition to electrophysiological data gathering, a microelectrode implanted into the brain could be used to deliver fluids to the brain and/or nervous system directly, such as medicine, or to gather liquid from the brain itself, in case of a medical necessity (such as cerebrospinal fluid analysis). Such probes have been demonstrated to be feasible, and integrated microvalves and pumps are currently being researched. [1] [8] [11] Current probes are nowadays capable of an output of 200 pL/s, and are vacuum shielded, which allows them to keep the rise in temperature of the surrounding tissue below 1 °C during operation. [12]

Besides the natural application in medicine for such probes as almost stand-alone units, an implanted microfluidic could also be useful in the electrophysiology of the brain itself, by inserting agents that can excite the brain and render spike detection amidst a hard to decode signal easier. An example of these techniques is currently being developed by the University of Michigan, Ann Arbor [12]. By injecting AMPA (an excitatory neural agonist) with the aid of such probes over a period of 10 seconds, spike detection increases dramatically regardless of the site it is injected into. [12]

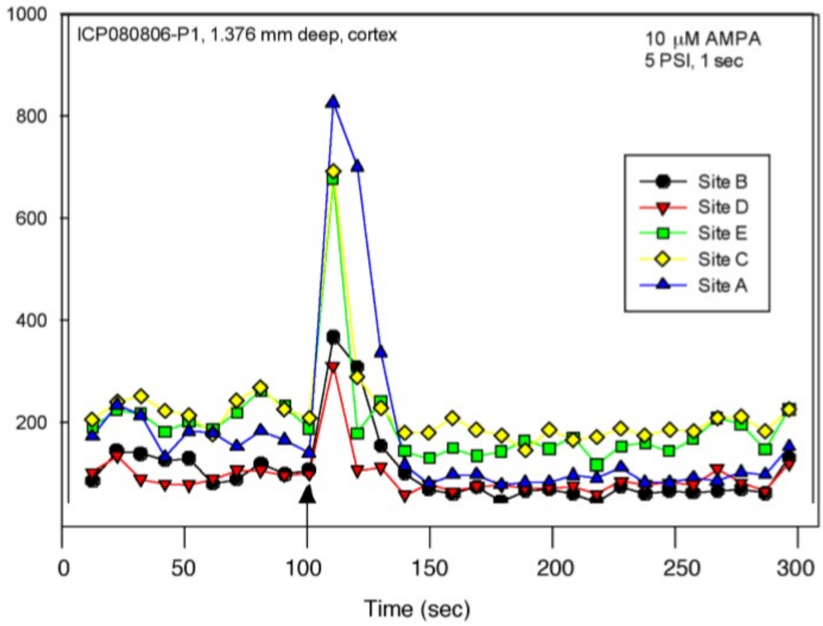

Figure 18: Neural spike counts in the presence of ten 100 ms injections of AMPA [8]

Therefore, the interest of developing a hybrid system incorporating electrodes for voltage detection as well as a set of microfluidic elements is justified not only for its medical applications, but also as a more pragmatic and "on site" way of improving signal detection without having to resort to the usage of amplification electronics, which in turn could aid the development of fully wireless BMIs.

3.2 Neuralink Possible improvements

In this section we discuss other sections of current BMI technology that must be improved upon in order to make it viable in a large scale. How does Neuralink take those challenges into account when developing their solutions ?

The BMI technology is just starting to implement the wealth of tools the miniaturization of semiconductor chips industry has advance in the past years.

Neuralink has been able to build a robust BMI based on the recent new tools created by engineers these past decades years. Advancement in surgical robotics, circuit miniaturization, and micro-fabrication has allowed Neuralink to build a new novel BMI. Before diving into Neuralink's BMI device we will introduce current tools being used to make BMI, their advantages and drawbacks.

4 Biocompatiblity

As previously before stated, any time a neural probe is inserted into the cortical tissue there is a risk of cellular death as one of the most sensitive tissues in the body are the brain and brain stem tissues. For this reason the selection of materials must be carefully considered. Testing for material's compatibility must follow strict protocols as written in the International Standard of Organization ISO 14708-3:2017 stipulating procedures to take in active implantable medical devices intended for electrical stimulation of the central or peripheral nervous system.

Biomaterial is a term that pertains to the body's acceptance of the material into the body, and the effects is has on the body's tissues. It looks at the long term impact on the surrounding tissue. The brain is delicate and cell death can be caused by functional changes between the cell and the cell's extracellular matrix. [13]

4.1 Probe design philosophy

In this section we will discuss electrode design, advantages and disadvantages of invasive implanting methods. The mechanical constraints to consider on chronically implanted neural probes. The failures of neural electrical recordings and opportunities to reduce them.

A clear channel input is primordial to create neuroprosthetic devices. Due to the small fluctuations in voltage a non-invasive approach can only give a general idea of the region of the brain being occupied. In order to provide sufficient information pertaining the status of external sensory signals the probe must be able to collect high fidelity channel counts. This has only been achieved with in brain implants. The nature of this implants further challenges the immune system's acceptance of the probe into the neural tissue.

As mentioned previously brain cells are extremely fragile to their surroundings. For this reason the electrode design must follow certain considerations to ensure a safe long term use in the brain is viable. The design of these neural probes are made with the goal in mind to be minimally invasive to the cell and surrounding tissue. This is done by two techniques. The first technique is the miniaturization of the implant. The second technique is through mechanical and material mimetism to its surroundings.

The miniaturization of the probe to microscopical dimensions is key to the body's acceptance of the implant. This diminishes the damage done to target neural structures during placement.

The second method is to camouflage the probe by structuring it with similar mechanical properties as the extra cellular tissue. Biocompatiblity is crucial to avoid long term formation of connective tissue between the neurons and electrodes. This means the density and stiffness should be similar to that of the neural tissue. This is necessary to avoid damage that could ensue from differential acceleration provoked by intrinsic motion (eyes,lungs or heartbeats) or extrinsic motion (walking). Typically low density probes of 1.35 $\frac{g}{cm^3}$ produce much less scaring than the equivalent high density probe of 21.45 $\frac{g}{cm^3}$ [9]. The brain's density is estimated at about 0.99 $\frac{g}{cm^3}$. [9]

Another approach is to coat the electrodes with a compliant nanocomposite hydrogel material. This could mitigate the mechanical difference between the soft tissue and the hard silicon. This technique has be able to transform a silicon probe with a Young's Modulus of 200 GPa to compliant structure with an average Young's Modulus of 49-70 GPa. [9]. A nanocomposite coating of 15 μm thick and Young's Modulus of 12 GPa.

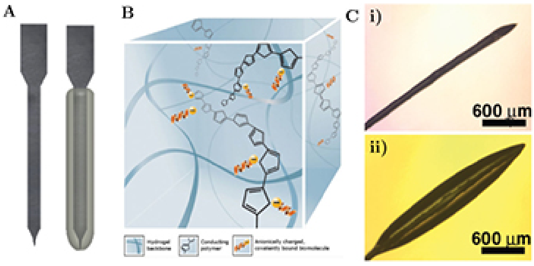

Figure 19: Silicon before and after multiple dip coating of hydrogel

Hydrogels are polymers that are commonly used in biomedical engineering. They are used due to their interesting characteristics to be flexible and bend with its surroundings.Furthermore hydrogels of natural materials such as fibrin, collagen, and alginate can be used to alleviate the immune response and advance cellular acceptance. Often synthetically-polymerized hydrogels such as PVA (polyvinyle alcohol) is used since the mechanical properties of this synthetic materials can be more easily fine tuned. Furthermore these synthetic electrodes can be enhanced with conductive polymers to improve electrical characteristics to better isolate potential differences, while still reducing the Young Modules of the probe. [9]

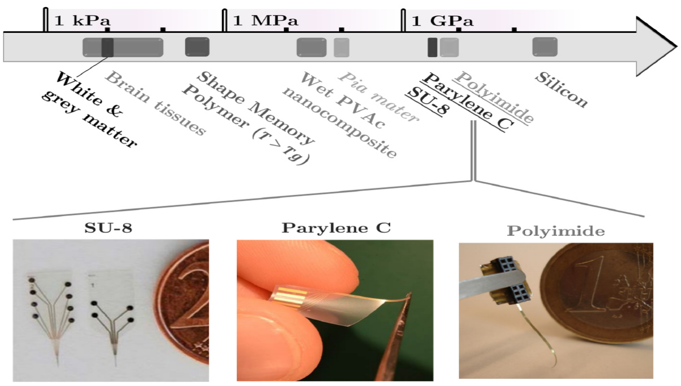

Figure 20: Young's modulus of brain tissues, and neural probe of the most common flexible substrates

5 Problems with miniaturization and final thoughts

In this section we will discuss some of the problems that arises from miniaturization of neural probes and the possible new solution ahead of making smaller probes.

Engineers and material scientist need to test the probes that are getting implanted into the tissue. With the miniaturization of the electrode probe the circuit wires are being reduced to the size of a few micro meters. The smaller the wire the higher the resistance is in this wires. With rising resistance the noise to signal ratio increases as does the heat.

Recent solution have aimed at replacing the thick steel wire with a new alternative: teflon insulated platinium iridium wire. The 25 μm insulated wire had a de-insulated tip of 1-2 mm that was implanted to the brain tissue. To further reduce interfacial impedance and thermal noise the tip was electro-depositing platinum black. [13]

5.1 Final Thoughts

As seen the task to create a functional BMI gathers many disciplines and challenges. Engineers are using their best tools to understand the best tool humanity ever had: our brains. The task is daunting as we are just starting to gather enough pieces of the puzzle to start making new discoveries of how the brain works, and how we could potentially fix or bypass areas that are malfunctioning. The ability to connect the brain to the outside world hints perhaps to the next stage of our human evolution. Similarly to how our outer cortex formed around our cerebellum to give human the processing capabilities to have cognitive thinking and reaction to the outside world, we see today electrodes connecting to the outside of the cortex to connect the brain with the processing and connecting of computers.

6 Conclusion

Neuralink is still at a very primitive stage of what it envisions to achieve. The current bandwidth is insufficient for a high speed communication with the brain. The current count of a few hundred electrodes is not enough to translate a thought or recreate complex motor functions. In order to restore full motor functionality to a patient the technology must be capable of getting higher bandwidth from the firing neurons. Then to become commercially successful the human interaction of the machine has to be taken into account. The bio-compatibility of these materials and surgical implementation of the product need to further advance to attract interest and confidence in these novel solutions.

Neuralink is trying to bring the pieces of a puzzle together to make a compelling image of what the future could look like. Neuralink's BMI succeeds others in the number of electrodes and thus individual neurons it is able to record. With more reading channels, signals interpreted by the computers can be refined to make more accurate assessments of brain activity. Neuralink's goal is to achieve this whilst making the procedure for this as noninvasive as possible. The development of a dedicated electrode insertion robot has allowed the placement of these probes to become safe and accurate. Neuralink as puzzled together the flexible polymer probes, dedicated electronics, and surgical robotic insertion system needed to make the most robust BMI.

This new BMI technology could open a new tool to understand and study the brain and brain related diseases. It also promises to offer a variety of new therapeutic possibilities for people with motor function injuries.

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A Annexes