Literature Study on the Technical Development of Invasive Recording Brain Computer Interfaces

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***Abstract*—Brain Computer Interfacing is a sprawling scientific field, with many competing designs in use or being tested. The goal of this project was to compile information about Utah Arrays, Michigan Probes, Neural Lace (also known as Mesh Electronics), Neuralink and Stentrode, and compare the positives and negatives of each design. Of especial interest were the parameters of material, number of electrodes, severity of foreign body response, heat generation, electrode depth, average size of measured action potentials and signal to noise ratio. The results of this comparison was as follows: Mesh Electronics and Stentrode are highly promising due to the complete avoidance of traditional foreign body response and cell death issues, however the latter trades these for the risks of long term usage of anti-coagulants. Utah Arrays have more problems than any of the other investigated designs in all parameters, including the contemporary Michigan Probe, although they both use the same primary material, silicon. There was found to be a severe lack of experimental studies rigorously comparing these two designs to each other, a lack that may become even more glaring once more of these designs become available for further medical studies.**

I. Introduction

Brain Computer Interfaces, or Brain Machine Interfaces, are devices which connect the central nervous system to external digital systems, using recording or stimulating electrodes placed in proximity to, or inserted into, the brain. These have long been used to broaden our understanding of the nervous system, and there are many ongoing medical projects using them to give someone further control over the outside world, such as communication while paralysed, controlling prostheses, etc [17].

Some of the biggest hurdles in designing them are tied to the effects of the probes on the surrounding cells, including the foreign body response. Through a combination of the usually traumatic insertion of probes, and their continued presence, they generally cause a chronic inflammation. In one study there was found to be a 10-50% decrease in neuronal density at distances up to 50 μm from the implant, with smaller decreases found up to the highest measured distances of 400 μm [39] [40] [43]. This reduction in measurable neurons negatively impacts device functionality, as does the high impedance of the scar tissue formed by astrocytes in response to this trauma [17].

One major factor for the magnitude and type of these reactions is material choice, especially parameters such as material flexibility, with major differences in Young's Modulus when compared to that of the neural tissue causing damage and measuring inconsistencies during micro and macro motions [10] [34]. Another is the risk of insertion causing puncturing of blood and/or cerebrospinal fluid vessels, which can have various negative effects, such as worsened inflammation [34].

There is also the factor of heat generation by probes and other devices inserted into the neural tissue, as temperature deviations greater than just one degree Celsius can have long term negative effects on the tissue, and deviations above three degrees Celsius has been found to cause necrosis and other abnormalities [18].

Other considerations of note when designing a Brain Computer Interface is the number of independently measuring electrodes, as a larger number of electrodes can, among other benefits, map electrical activity over an area as opposed to singular points, which is of great use for some scientific studies [28].

Due to these and many more factors of consideration, a vast array of different designs with their own advantages and disadvantages have been devised, whether penetrating the neural tissue, or placed within nearby vasculature. Although differing heavily in their makeup, there are similarities that hint towards many of them originally being based on the same designs, akin to an evolutionary tree. Yet, it is simultaneously difficult to get an overview of what the options are, and which designs are better suited for what, with many papers choosing just one to use, with no reasoning provided for why that one was chosen. Thus the point of this project was extending the evolutionary analogy further, and answering the question "What are the current metaphorical 'evolutionary branches' of reading invasive Brain Computer Interfaces, what are their strengths and weaknesses, and how did they 'evolve' to be such?". For this purpose a selection of notable Brain Computer Interface designs was described in history, purpose and design, and an attempt was made to trace backwards to find what previous designs they are based on, and they were compared in various ways to determine which are more suitable for general use. A short analysis of the materials used for these designs from a sociological and environmental perspective was also performed.

II. Method

The systematic searches performed over the course of this literature study are listed in Table I,II.

During project planning five metaphorical "Evolutionary Branches" of Invasive Recording Brain Computer Interface design were selected to control the scope of the project. They were:

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- Utah Arrays
- Michigan Probes
- Neural Lace
- Neuralink
- Stentrode

Preliminary literature searches were performed using the search terms ”Utah Array”, ”Michigan Probe”, ”Neural Lace”, ”Neuralink” and ”Stentrode” in individual searches on the Scopus search engine, in order to find relevant key words for later systematic literature searches, that would cover a majority of papers discussing each probe.

For gathering technical and general information, these collections of keywords were used in the search engines Scopus, Web of Science, SpringerLink and IEEExplore. For each probe results were culled to the ten most cited texts published within the past 20 years. This restriction was meant to reduce the articles to a manageable volume, but likely removed useful articles about the early development of the probes, and less cited, or very recent, analyses of it. The former issue was hopefully alleviated by articles generally referencing earlier key articles on the topic, such as the articles which initially coined the terms and defined the design.

The identified articles were also screened for studies wherein the probe was used to investigate other phenomenon, as opposed to investigating or discussing improved probe design, in an attempt to find differences in main use-cases of each ”branch”.

To find the early history of each probe, the scientist or team that initially created it was found through various Google searches, where-after their bibliographies were sorted by age, and their earliest relevant papers were read, until the articles whose methods were cited by the articles found during the previous round of searches was identified.

The probes were compared on the parameters of material, number of electrodes, severity of foreign body response, heat generation, electrode depth, average size of measured action potentials and signal to noise ratio. After the systematic search any remaining blanks within these topics were investigated through searches on the Scopus search engine for the keywords identified for the probe design, combined with relevant keywords for the missing information.

III. Technical Descriptions

A. Utah Intracortical Electrode Array

The Utah Intracortical Electrode Array, also known as Utah Electrode Array, Utah Array, UEA or UIEA, is an array of single channel spike electrodes mounted orthogonally to a plate, which was ”originally developed to provide focal stimulation of visual cortex as a means to create a functional sense of sight for the blind” [30].

It is named after the University of Utah, where it was developed by Richard Normann *et al.*. They presented small initial studies performed as part of the development of the array at the Annual International Conference of the IEEE Engineering in Medicine and Biology Society 1988 [32], 1989 [31] and 1990 [41], before it was finally described in detail, in an article in 1991, which also went into much detail about the manufacturing methodology [8].

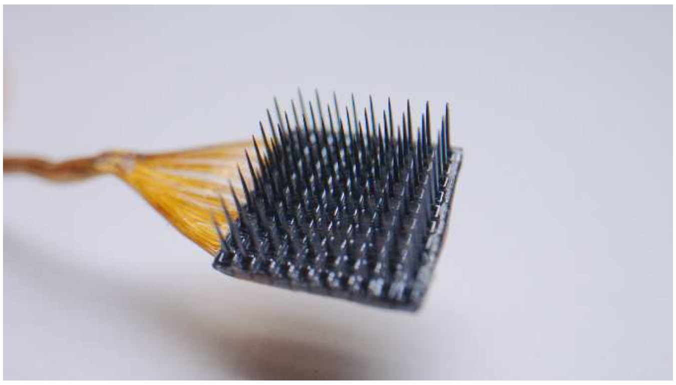

Fig. 1. Photo of Standard Utah Array, from the BlackRock Neurotech product page, (https://blackrockneurotech.com/products/utah-array/), Copyright Blackrock Neurotech (BlackRock Neurotech was contacted for a clarification on the which year they gained copyright over the image, but did not respond), used with permission.

At this point it was not referred to as an Utah Array, but it bears mentioning that this article [8], with more than 600 citations, has been cited in more papers than every article found through the searches performed for Utah Array related articles, even when unrestricted by year. There is one exception to this, a 2007 article penned by a different group of researchers affiliated with the University of Utah, which added a local circuitry to compress the signal, and a wireless transmitter [14].

1992 Normann *et al.* published another article [16] about their new manufacturing technique, based upon various issues found in the previous study, with the primary change in design being changing the insulation between electrodes to glass instead of oppositely charged silicon. The array was featured on the Annual International Conference of the IEEE Engineering in Medicine and Biology Society once more that year [29], marking the first instance of the design being referred to as an Utah Intracortical Electrode Array in academic literature.

Normann would go on to found the company Bionic Technologies [24] to commercialize the Utah Array, which was eventually acquired by Cyberkinetics Neurotechnology. The latter later gained two Investigational Device Exemptions from the FDA to initiate human trials for BrainGate, a brain computer interfacing system based upon Utah Arrays, with the goal of giving paralyzed people back the ability to control part of their environment. Partway through the development of BrainGate the company was split and acquired by Blackrock Microsystems and The BrainGate, with the former gaining the rights to much of the hardware, and today still acting as the main manufacturer of Utah Arrays, and the latter acquiring the rights to the Braingate concept itself. Notably, reports from BrainGate’s clinical trials include the device and system still being functional 5 years after the array had been inserted [17]. It has also been successfully used in experiments to recreate the sensation of extremely limited sight for blind people, through stimulation of the visual cortex [11].

The exact specifications of the Utah Array vary greatly across the many articles published by Normann *et al.* [28] [16]

[30] [33]. The arrays are generally comprised of a 10*10 grid of p-type silicon electrode needles jutting out 1.5 mm from a 4*4*0.2 mm plate, made up of the bases of the electrodes, separated by dielectric glass for electrical insulation, see fig 1. The electrodes are 60-80 μm wide at the base, and end in a sharpened tip, varying lengths of which is coated with thin layers of highly electrically conductive metals, which usually includes platinum. The rest of the electrode, and sometimes the entire rest of the array, is coated by some electrically insulating polymer. The backside of the plate has a metallic coating on the bottom of each electrode to be used as access ports.

The 1989 conference paper [31] describes an array that is significantly smaller than the rest of these early variations, measuring only 0.4*0.4 mm, yet is otherwise very similar in measurements, including the bases of the electrodes measuring 60 μm. However there is no mention of drastically changing size in it or following papers, indicating that the difference might be due to a decimal error.

Downsides of the Utah Array design include that it requires a more forceful insertion apparatus than other probe designs, due to the comparatively large total surface area of the spikes, increasing the insertion trauma [28]. This is exacerbated by the fact that the large amount of electrodes makes it very difficult to place the array such that it does not pierce any blood vessels, and increases pressure and strain on surrounding tissue [27]. These factors combine to greatly increase the scale of the foreign body response, and increase the risk of loss of significant amounts of cortical tissue, which in rats have been shown to be similar to ischemic and hemorrhagic stroke [27]. There have also been cases in larger animals of the arrays sinking into the depression forming in the cortex [27]. These factors combined cause the sensor to have more issues with connection to the neurons, with one study finding that 40% of the electrodes in their array were unable to meaningfully record neuronal activity after 6 months in the brain of a cat [20]. Due to these issues there is a growing call to continue researching other alternatives [20].

B. Michigan Probe

Michigan Probe, or Michigan Array, refers to a general design concept popularised by Kensall D. Wise at the University of Michigan [23]. In a Michigan Probe the electrodes are embedded into a flat silicon prong, leading to exposed electrode surfaces spread around one side of the prong's tip, usually on the the same flat surface. This design often includes multiple spikes at the end of the prong, and multiple electrodes per spike.

What eventually became the Michigan Probe was first outlined in a paper published by Wise *et al.* 1970, while he was studying at Stanford University [23]. The purpose was to make the design and technical details of neural electrodes more consistent and reproducible, as this was a significant issue with contemporary neural probes, as well as to create a probe with a more flexible design that can easily be changed to fit specific purposes [48].

These advancements were accomplished by using micromachining technology developed for integrated circuitry to create flat tapered prongs of silicon, about 50μm thick, upon which one to three gold electrodes, surrounded by a nickel layer for improved bonding, were insulated by silicon oxide. All surfaces of the probe, with the exception of the tip, were also coated in an insulating lacquer. The biggest difference between this first design and what is now known as a Michigan Probe is the fact that the electrode tips were not exposed panels along the flat side of the prong, but rather tips that jut out 10 to 50 μm from the end of the prong (the size of the uninsulated recording areas was unspecified, but areas as small as 15 μm^2 had been achieved). These thin tips became problematic in their physiological evaluations, with 5 instances of a tip breaking off during the 60 experimental insertions performed, although the authors noted this to be a satisfactorily low rate of error [48].

Wise *et al.* went on to experiment with entirely different solutions to these problems for the next decade, including a glass micro-pipette with thin metallic films creating multiple electrodes attached to the outside [38]. In 1985 they returning with a new version of this Proto-Michigan probe [26], now far more reminiscent of its modern incarnation, with recording sites exposed on top of the silicon prong, as opposed to jutting out from it, and thanks to this there were no instances of the probe breaking during several hundred experimental insertions. Gold was still used for the recording sites, and notably the recording sites were still at the edges of the prong surface, as opposed to fully on the flat surface.

A study published by Wise *et al.* 1986 [6], which builds upon the former, features probes with the recording sites exposed on various locations on the flat surface of the prong, and probes with multiple prongs, thus reaching what is today recognisable as a Michigan Probe.

Between 1981 and 2006 Wise's team had a grant from the USA National Institute for Health, during which time they supplied nearly 10,000 Michigan Probes for various neuroscience laboratories, which helped popularize the term and design [23].

The earliest found usage of the terms Michigan Probe", "Michigan Array" or "Michigan-style" in the literature, according to a Scopus search, was in 2003 by a conference paper for a study investigating the usage of hydrogels to improve the foreign body response evoked by it [46].

The company NeuroNexus was founded 2004 by members of Wise's team [23], and is the seller of Michigan Probes used for many studies [47] [13]. Their catalogue includes a large variety of different Michigan probes, with designs ranging from 1 to 8 prongs and 16 to 256 electrodes, although 16 and 32 electrode probes are most common. Prong length vary between 2 and 10 mm and they also offer a custom probe design service [1].

Some studies indicate that long term viability of Michigan probes improve with recording sites placed on the edge of the probe, however whether this is due to fibrous encapsulation, cell death or some other faction is unclear [21].

There have been multiple studies attempting to use Michigan Probes to gain a greater understanding of the brains of rats and mice [49] [35].

C. Neuralink

Neuralink, founded 2016 by Elon Musk *et al.*, is a company dedicated towards the creation of implantable Brain Computer Interfaces [3]. Technical information about the specifics of Neuralink's device, called The Link, is sparse, with the company only having published one paper about it. It describes two out of 20 attempted designs for the probe end, with no indication of which design was eventually chosen, and with the descriptions on their website contradicting both in regards to the number of threads and electrodes per thread [25]. There is also a lack of information and specificity about updates and changes to it on their website [4].

Outlined in that singular paper is a probe consisting of 48 or 96 threads, each 4-6 μm thick and containing 32 electrodes ending in recording sites spread along the end of the thread. This gives a total count of 1536 or 3072 electrodes. The internal electrical conduits of the electrodes were made of gold, and the main difference between the designs where whether their tips were coated with iridium oxide or polystyrene sulfonate, but the material and design of the rest of the thread is unclear [4].

One of the biggest advances to the field brought by Neuralink is the creation of a surgical robot that inserts the threads, into an exposed brain, deftly avoiding blood vessels, which could potentially significantly reduce the foreign body response by reducing the risk of bleeding. However so far there have been no studies published on the foreign body response evoked by this procedure, or the safety of the machine [4].

D. Neural Lace/Mesh Electronics

It was found that Neural Lace is seldom used in the literature, and was dubbed by Ian M. Banks in his series of Science Fiction novels "The Culture". It refers to a concept of an extremely thin electrically conductive mesh, that is implanted under the skull, and is from there able to pick up neural activity that is read by a connected device [19], and is in academic circles more commonly known as Mesh Electronics. This term, and the usage of the concept within real life neurology, was pioneered in 2015 by Jia Liu and his colleagues at Harvard University [22], while building upon research done a few years prior, during his PhD. At the time, Liu *et al.* had already created the probe design [44], inspired by the explosion of flexible electronics that had occurred within the previous half a decade [2].

It is a thin mesh of flexible metallic and silicon nanowire, combined with parts of extracellular matrix, giving it a minimal immune response. Only a small initial foreign body response was found shortly after the insertion, which abated within 4 weeks of insertion, continuing to be non-existent for at least 3 months. It was also found that the neural cells grow back around and through the mesh, penetrating the holes in it [50]. This mesh is injected with a syringe directly into the brain tissue, moving it during injection such that it is draped out in the direction of the syringe, see fig 2 [22].

E. Stentrode

Stentrode, short for Stent Electrode Array, is an endovascular neural probe design developed by Synchron and originally presented in 2016 [45]. The central premise of the Stentrode is expanding the function of the vascular stents already in regular clinical use to treat vascular and neurological conditions, to also record electrical signals from the brain, through the vascular walls, which it over time incorporates into [45]. See figure 3.

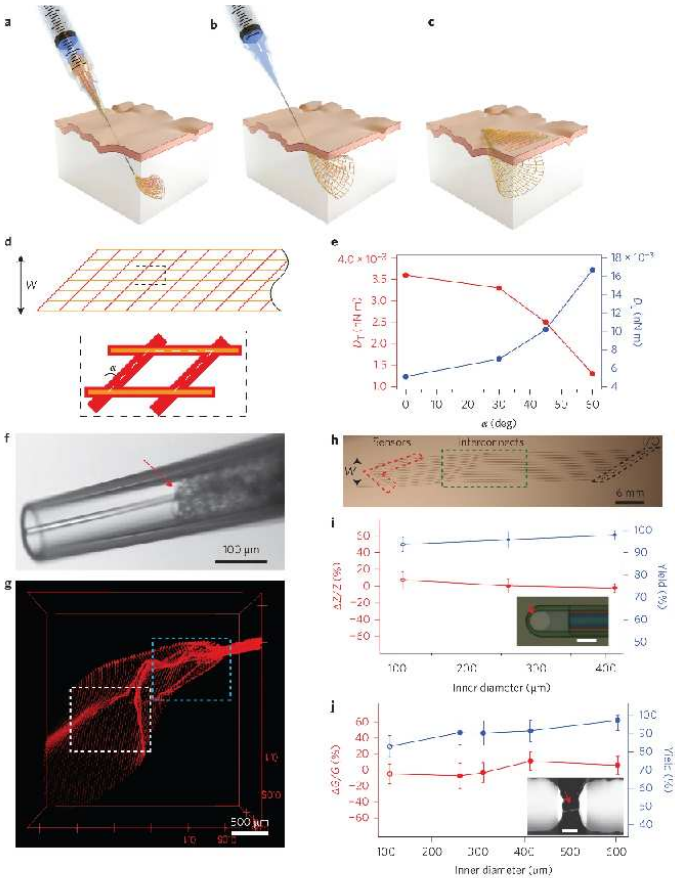

Fig. 2. Figure 1 of "Syringe-injectable electronics" by Jia Liu *et al.*, 2015, Nature Nanotechnology, 10, s. 630, https://doi.org/10.1038/nnano.2015.115, Copyright Nature 2015, used with permission.

The original probe design consisted of wires with platinum electrode tips, wrapped around Nitinol vascular stents and attached with medical adhesive, both commercially available. The probe was tested for 190 days in sheep, achieving stable signal quality after the first 2 weeks, with the stent being partially incorporated into the vessel walls within a week. This signal quality was also shown to be only of marginally lesser quality than a commercially available penetrative array which was of a design not covered by this paper. During these trials, anti-coagulants were regularly administered, which have other negative effects. and the endothelial tissue still expanded significantly inwards, restricting blood flow, however this did not cause any blood vessels to close completely. Details on the scale of these constrictions were sparse. [45] [15]. The wires from the Stentrode out to the external devices were often fatigued from the animals' motions, and was thus in later studies replaced by the more durable cables commonly used for pacemakers [45]. One of the the big upsides of the Stentrode design is that due to the insertion through blood

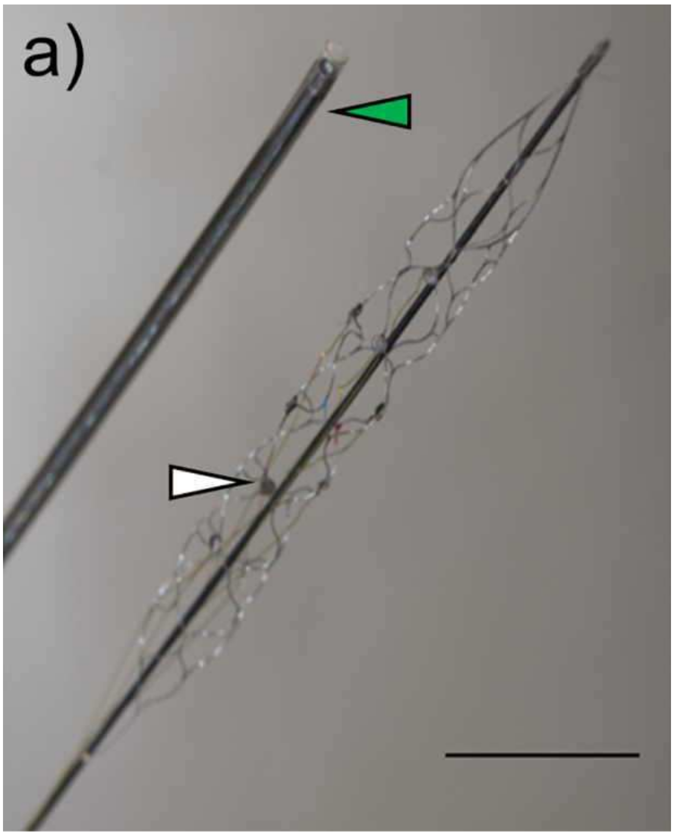

Fig. 3. Stentrode (white arrow) and delivery catheter (green arrow). Scale bar 1 cm. From ”Visual evoked potentials determine chronic signal quality in a stent-electrode endovascular neural interface” by G Gerboni *et al.* 2018 *Biomed. Phys. Eng. Express* 4 055018 , https://doi.org/10.1088/2057-1976/aad714 , used under CC BY 3.0 / Cropped from original

vessels, it can access deeper brain regions inaccessible to most other probe designs. On the other hand it is restricted by size of the blood vessels, requiring a minimum width of 1.7 mm.

In 2019 and 2020 it was tested in a total of two humans, this time with 16 electrodes, with anti-platelet therapy planned for at least a year after insertion. An open pathway into the body was avoided by having a wireless connection port at the chest, charged inductively and communicated in infrared. During the 340 combined days of the stentrode being implanted in the two test persons, there were no adverse events related to the device recorded. Outside the number of electrodes, other specifics of the probe design were unmentioned [36].

A clinical study for long term use of the probe was started 2021, with preliminary results after one year showing that of the four subjects implanted with the device, none had experienced any ”serious adverse events”, or had any blood vessels close [7].

IV. Comparative analysis

In addition to the following comparisons, it is also worth noting that Michigan Probes and Utah Arrays are the only designs on this list that have been used as a tool for further research in neurology. It seems papers using the other designs are so far only focused on evaluating and improving the design itself, which makes it difficult to gauge the reception of the other designs by the scientific community, and discuss differences in how they are used in practice.

Specific information about Stentrode, Mesh Electronics and The Link is sparser, as they are much newer devices than Utah Arrays and Michigan Probes, and thus naturally have had much less time for scientific discourse and study.

A. Comparative Studies

There is a general lack of rigorous scientific comparison between these probe designs. In 2009, Ward *et al.* attempted to perform an in depth comparison between Utah Arrays, Michigan Probes, and some other designs, on rats, meant as a pilot study for future comparisons. There were two kinds of Utah Arrays, tipped with iridium oxide or with platinum. The Michigan probe recording sites were made of iridium, and had 4 prongs with 4 electrodes each. No clear superior probe was found, and the signal to noise ratio of all probes were found to be similar, although they noted multiple issues with the study. They examined the increase of impedance over the period each probe was inserted, as a measurement of fibrous encapsulation, stained slices targeting specific proteins relevant to the immune response, and performed routine measurements of individual neuronal activity. They found that the Utah arrays had the highest spikes in impedance (and thus immune response) after insertion, and a large amount of fibrous growth, theorized to be closely linked to the severe bleeding in a majority of cases. They found little notable difference in performance between platinum and iridium oxide tipped Utah Arrays relevant for reading Brain Computer Interfaces. The Michigan probes were noted as having the least variability between recording sites, which was attributed to good quality control by NeuroNexus [47].

These findings however have limited usability, as the issues with the study included a limited budget, which restricted them to a low number of replicates for each design, and the early termination of measurements for a majority of the rats equipped with Utah Arrays. There were also systemic issues with comparing the two designs, as the surgical procedures to insert them varied vastly. The Utah Arrays requiring a rapid forceful insertion, while the Michigan probes were able to be inserted far slower and more carefully [47], thus reducing foreign body response.

B. Parameter comparison

A summarized table of all found parameters can be found in the appendix, see table III.

There was a lack of public information on the parameters of heat generation, average voltage amplitude of measured action potentials and signal to noise ratio for most of the designs. This makes it very difficult to compare the designs on those grounds, leaving the parameters of material, number of electrodes, severity of foreign body response and electrode depth.

The parameter of material used is difficult to systematically compare, as it varies heavily between instances of the same design for Utah Arrays and Michigan Probes, is partially unknown for The Link and Stentrode, and has not yet been codified in the case of Mesh Electronics. One consistent material element in Utah Arrays and Michigan Probes is that the segments inserted into the cortex primarily consist of silicon, which has a significantly higher Young's modulus than the soft neural tissue it is inserted into. This mismatch increases the physical strain and damage upon the tissue, causing inflammation and/or cell death [12]. While the thread material of The Link is unknown, it is stated in their article [25] that one of the aims of the design is to avoid this issue, calling The Link "a flexible, scalable brain-machine interface".

A large number of individual recording electrodes within a probe is generally desirable to increase spatial precision. For Utah Arrays [34] (standard 100 electrodes) and The Link (1536 or 3072 electrodes), this requires a significant increase in the cross-sectional area piercing through the brain, which is a significant issue for Utah Arrays due to the decreased accuracy during insertion, and increased trauma, but less so for Neuralink due to their surgical robot and separately inserted threads. For Michigan Probes (16-256 electrodes in Neuronexus' catalogue [1]), more electrodes can be added without too much trouble by adding additional internal electrode channels and exposed surfaces upon the surface [34]. For Stentrode (unknown number) there may be an upper limit to how many electrodes can be incorporated into the stent before it significantly impacts the compressability that is vital for insertion. Mesh Electronics (unknown number) has electrodes woven into its fundamental structure, which may make it difficult to add additional electrodes at a location or over an area without directly increasing the volume of mesh inserted, however this may be less of a problem due to the good foreign body response detected from the insertion of a mesh. Of the designs with known number of electrodes, The Link has by far the highest number of individual recording electrodes, but these are not necessarily located in the same area, being distributed across 48-96 threads, and the other probe designs can also theoretically be combined into arrays to reach similar numbers.

Regarding how deep into the cortex the designs can measure, Utah Array has the shortest reach, only being able to measure at a depth range of 0.5 to 1.5 mm. Michigan Probes on the other hand can be made much longer, having a range of 2 to 15 mm [9]. The effective depth range of The Link and Mesh Electronics is unknown, and for Stentrode it is irrelevant, due to the vascular insertion method. While Michigan Probes and likely The Link have significantly longer spikes than Utah Array, they might potentially also be able to measure closer to neurons 0 to 0.5 mm from the surface of the cortex than it, due to the exposed electrodes at the side of the spikes, as opposed to only measuring from the tip of the spikes. Neuronexus' custom design services also means that the specific depths of the electrodes can be customized, in case there is need for measuring neurons at a very specific depth. It is clear from the literature [47] [17] [34] that depth is a factor of note, however there is little information regarding which depth ranges are important to measuree.

When it comes to magnitude of foreign body response, Mesh Electronics have limited studies investigating it, but in those that have been published, it has the least foreign body response of these designs, with measurable foreign body response only in the first weeks after insertion, and no scarring over 4 months of it inserted into a brain [50]. Utah Arrays have significant issues with foreign body response, due to the increased trauma and risk of bleeding, and is known to cause the most scarring and cell death, followed by Michigan Probes, which have less severe issues. It is unknown how big an issue this parameter will be for The Link, but considering the combination of having significantly reduced inserted area in comparison to the former two, and the surgical robot specifically designed to help insert them without damaging blood vessels, it should have milder foreign body response than them. Stentrode is difficult to compare on this parameter, as the foreign body response of traumatic insertion directly into the cortex is very different to that of smooth netting inserted into a blood vessel.

V. Discussion

A. *Author's Thoughts Regarding Design Comparison*

Mesh Electronics is the most promising design for long term use, due to significantly reduced issues with foreign body response compared to Utah Arrays, Michigan Probes or The Link, and not causing blood vessel constriction, nor requiring the user continuously take anticoagulants, like Stentrode. However, due to building upon science that has been medically tested for a significantly shorter period of time, it is seemingly much farther from being commercially available, and there may remain multiple undiscovered issues with usage over periods longer than one month, or in large scale production.

Stentrode is likely the closest of these designs to being commercially available, as it is partway through phase 1 of clinical trials (for the only other design to have entered clinical trials, the Utah Array, the process seems to have stalled or been ended partway through). Furthermore it has various other advantages over Utah Arrays, Michigan Probes and The Link. However, the need for long term anti-coagulants is a significant issue for long term use.

For present-time neurological studies, the choice currently stands between Michigan Probes and Utah Arrays, with the more suitable choice depending on the requirements of the study. If it is a short term study of a large 2d surface of the cortex' outermost layers, Utah Arrays may be preferable, due to the large number of electrodes distributed along the dimensions of the surface. On the other hand, for longer term studies requiring access to deeper tissue, very specific depths, or measurements at multiple depths, and any studies on humans, Michigan Probes may be preferable, due to the lower damage to the cortical tissue and foreign body response, the ability to distribute the electrodes more freely, and place them deeper.

However, the very low number of experimental comparative studies featuring multiple of these designs is a major restriction when it comes to coming to a conclusion on many of these questions. This is perhaps the most important avenue going forward when it comes to investigating benefits and downsides to each of these probes.

B. Failure of Original Project Plans

Originally this paper was intended to investigate how invasive Brain Computer Interfaces had evolved over the decades, and what ”closest common ancestor” these branches shared, when it came to the history of their technical development, culminating in a graphical representation in the style of an evolutionary tree.

However, once the project started it became apparent that these ”branches” were far more disconnected or ”distantly related” than expected. The technical development of Mesh Electronics and vascular electrodes like Stentrode has also been almost entirely separate from the development of the penetrative designs (Utah Array, Michigan Probe, The Link). The development of vascular electrodes has been almost entirely linear, starting in 1973 when Penn *et al.* [37] built upon a magnetically guided vascular probe recently developed at their lab to design the first vascular intracranial EEG electrode, in an effort to localise epileptic foci, with some overview papers drawing clear timelines of the field’s development [42].

For the penetrative designs, it was attempted to investigate the sources referenced regarding probe design in their keystone papers, then following the trail of references regarding which paper’s design was being improved upon in each paper back to find that ”closest common ancestor”, however this ran into multiple problems:

- Many papers were highly unclear when it came to explaining what they had changed compared to previous studies, which previous studies, or why, or comment on what effects their changes had had on the outcome.
- Many old papers mention devices by name and company, but do not provide adequate details about them for analysis, making it very difficult to find the relevant information about devices which are no longer on the market, or otherwise have no web presence.
- Multiple seemingly important references were to papers in other languages, such as French or German.

Thus this pursuit was abandoned due to time constraints after more than 50 papers had been screened, and the unclear trails had been followed to papers published before 1950.

The initial selection of designs to be investigated was highly arbitrary (simply being a list of the notable designs the author had heard of at the time of project planning), seemingly missing multiple popular designs that have been used in comparative studies with the ones chosen, and including Neuralink, for which extremely little consistent information is available.

When trying to explore what purposes different designs are used for, it also become a problem that many papers using these designs do not give any reasoning for their choice of probe. This leaves the reader to wonder whether it is particularly well suited for the purpose, or if it was just the specific design they had most easy access to, or were most familiar with.

It might be a good approach for a larger metastudy to contact a large number of researchers publishing papers with these probe designs with survey forms about which probe types they use, for what, and why.

VI. Analysis of Environmental and Sociological Sustainability

It would be of great interest to see an in-depth study performed upon the materials often used in neural probes, and their varying issues from a sociologically and environmental sustainability angle. However due to to the large variability of materials used for variants for each probe, the lack of information regarding the materials of some, and the authors little experience in this kind of analysis, such an analysis within this paper was difficult.

None of the specific materials generally used for any of these designs require petrochemical processes to manufacture, with the potential exception of the unspecified polymer used in The Link to achieve a low Young’s Modulus, however it is possible that some of the insulating covers, adhesives, and other chemical compounds used in specific iterations of the designs do. It may also be that some of the manufacturing methods used require very high amounts of energy, or otherwise are more environmentally straining than others. Evaluating this would require significantly more transparency from each research group.

Gold is defined as a conflict mineral by the European Union [5], which means a significant amount of the gold mined in the world involves violations of the workers human rights, or finance the inhumane actions of local warlords. Gold is heavily used in many of these designs for its good electrically conductive properties, and it is unclear if the producers of these probes made sure their gold did not stem from such sources.

Shared by all of these designs is that depending on where the data generated by the probes is sent, ethical questions of privacy arise, as combinations of these recordings and information about the subjects surroundings at the time could give away information the subject, is for any myriad reasons, unwilling to share.

VII. Conclusion

The technical evolution of Brain Computer Interfaces is a muddied, disjointed tale, which has given rise to many vastly different designs with different strengths and weaknesses. Thoroughly establishing how it has developed over time, and at what point different concepts branched off is far outside the scope of a Bachelors Thesis.

It was found that that Stentrode and Mesh Electronics hold great promise and that the design most heavily mentioned and cited in the literature, the Utah Array, is generally outperformed in almost every parameter by an older design the Michigan Probe.

VIII. Afterwords

The majority of the research for this paper was done during the fall of 2022, thus some facts presented in it are out of date, for example Neuralink has since announced that they have been approved by the FDA to begin clinical trials.

Unsuccessful attempts were made to gain permission to use images of the Michigan probe or from Neuralink.

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APPENDIX

TABLE I
TABLE OUTLINING SEARCHES PERFORMED DURING THE SYSTEMATIC SEARCH STEPS, PART 1

Search Engine	Search Terms	Articles	Notes	Search Date
Pubmed	invasive brain-computer NOT non-invasive	222	Earliest result from 2000	2022-09-23
Pubmed	stentrode	16		2022-09-07
IEEE Xplore	("Publication Title":"Utah Array") OR ("Document Title":"Utah Array") OR ("Abstract":"Utah Array") OR ("Publication Title":"utah electrode array") OR ("Document Title":"utah electrode array") OR ("Abstract":"utah electrode array") OR ("Publication Title":"utah intracortical electrode array") OR ("Document Title":"utah intracortical electrode array") OR ("Abstract":"utah intracortical electrode array")	38	restricted to 2003-2022 due to no articles from 2002 2 with 82 or more citations according to on-site data	2022-09-29
SCOPUS	(TITLE-ABS-KEY ("Utah Array") OR TITLE-ABS-KEY ("utah electrode array") OR TITLE-ABS-KEY ("utah intracortical electrode array")) AND (LIMIT-TO (LIMIT-TO (PUBYEAR , 2022) OR PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010) OR LIMIT-TO (PUBYEAR,2009) OR LIMIT-TO (PUBYEAR,2008) OR LIMIT-TO (PUBYEAR,2007) OR LIMIT-TO (PUBYEAR,2006) OR LIMIT-TO (PUBYEAR,2005) OR LIMIT-TO (PUBYEAR,2004) OR LIMIT-TO (PUBYEAR,2003) OR LIMIT-TO (PUBYEAR,2002))	131	10 with 82 or more citations according to on-site data	2022-09-29
Web of Science	"Utah Array" (Topic) OR "utah electrode array" (Topic) OR "utah intracortical electrode array" (Topic)	84	4 with 82 or more citations according to on-site data	2022-10-03
SCOPUS	(ALL ("Utah Array") OR ALL ("utah electrode array") OR ALL ("utah intracortical electrode array")) AND (LIMIT-TO (PREFNAMEAUID , "Normann, R.A.#7007113176"))	47		2022-10-07
SCOPUS	(TITLE-ABS-KEY ("Michigan Probe") OR TITLE-ABS-KEY ("Michigan Array") OR TITLE-ABS-KEY ("Michigan-style") OR TITLE-ABS-KEY ("Neuronexus Probe ")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010) OR LIMIT-TO (PUBYEAR,2009) OR LIMIT-TO (PUBYEAR,2008) OR LIMIT-TO (PUBYEAR,2007) OR LIMIT-TO (PUBYEAR,2006) OR LIMIT-TO (PUBYEAR,2005) OR LIMIT-TO (PUBYEAR,2004) OR LIMIT-TO (PUBYEAR,2003) OR LIMIT-TO (PUBYEAR,2002))	91	10 with 53 or more citations according to on-site data	2022-10-08
Web of Science	"Michigan Probe" (Topic) or "Michigan Array" (Topic) or "Michigan-style" (Topic) or Neuronexus Probe (Topic)	67	No results from before 2003 4 with 53 or more citations according to on-site data	2022-10-08
IEEEXplore	(("Publication Title":"Michigan Probe") OR ("Document Title":"Michigan Probe") OR ("Abstract":"Michigan Probe") OR ("Publication Title":"Michigan Array") OR ("Document Title":"Michigan Array") OR ("Abstract":"Michigan Array") OR ("Publication Title":"Michigan-style") OR ("Document Title":"Michigan-style") OR ("Abstract":"Michigan-style") OR ("Publication Title":"Neuronexus Probe") OR ("Document Title":"Neuronexus Probe") OR ("Abstract":"Neuronexus Probe"))	21	restricted to 2003-2022 due to no articles from 2002 1 with 53 or more citations according to on-site data 1 with 70 citations by patents, thus deemed of note.	2022-10-08

TABLE II
TABLE OUTLINING SEARCHES PERFORMED DURING THE SYSTEMATIC SEARCH STEPS, PART 2

Search Engine	Search Terms	Articles	Notes	Search Date
SCOPUS	(TITLE-ABS-KEY (”Michigan Probe”) OR TITLE-ABS-KEY (”Michigan Array”) OR TITLE-ABS-KEY (”Michigan-style”) OR TITLE-ABS-KEY (”Neuronexus Probe ”)) AND (TITLE-ABS-KEY (heat) OR TITLE-ABS-KEY (temperature) OR TITLE-ABS-KEY (thermal))	3		2022-10-14
SCOPUS	(TITLE-ABS-KEY (”Michigan Probe”) OR TITLE-ABS-KEY (”Michigan Array”) OR TITLE-ABS-KEY (”Michigan-style”) OR TITLE-ABS-KEY (”Neuronexus Probe ”)) AND (TITLE-ABS-KEY (fbr) OR TITLE-ABS-KEY (biocompatibility) OR TITLE-ABS-KEY (biocompatible) OR TITLE-ABS-KEY (inflammation) OR TITLE-ABS-KEY (astrogliosis) OR TITLE-ABS-KEY (”immune response”))	13		
SCOPUS	(ALL (”Michigan Probe”) OR ALL (”Michigan Array”) OR ALL (”Michigan-style”) OR ALL (”Neuronexus Probe ”)) AND (ALL (”Utah Array”) OR ALL (”utah electrode array”) OR ALL (”utah intracortical electrode array”))	12		2022-10-15
SCOPUS	ALL (”Utah Array”) OR ALL (”utah electrode array”) OR ALL (”utah intracortical electrode array”)	1447		2022-10-18
SCOPUS	ALL(”Michigan Probe”) OR ALL(”Michigan Array”) OR ALL(”Neuronexus”)	105		2022-10-18
SCOPUS	TITLE-ABS-KEY (”Neural Lace”)	2		2022-10-18
SCOPUS	(TITLE-ABS-KEY (”Neural Lace”) OR TITLE-ABS-KEY (”mesh electronics”)) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010) OR LIMIT-TO (PUBYEAR,2009) OR LIMIT-TO (PUBYEAR,2008) OR LIMIT-TO (PUBYEAR,2007) OR LIMIT-TO (PUBYEAR,2006) OR LIMIT-TO (PUBYEAR,2005) OR LIMIT-TO (PUBYEAR,2004) OR LIMIT-TO (PUBYEAR,2003) OR LIMIT-TO (PUBYEAR,2002)))	24	8 with 33 or more citations according to on-site data	2022-10-18
IEEEXplore	(”Document Title”:”mesh electronics”) OR (”Publication Title”:”mesh electronics”) OR (”Abstract”:”mesh electronics”) OR (”Document Title”:”Neural Lace”) OR (”Publication Title”:”Neural Lace”) OR (”Abstract”:”Neural Lace”)	2	0 with 33 or more citations according to on-site data	2022-10-18
Web of Science	“Neural Lace” (Topic) or “Mesh Electronics” (Topic)	33	10 with 33 or more citations according to on-site data	2022-10-18
SCOPUS	(TITLE-ABS-KEY (”NeuraLink”)) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002))	20	10 with 2 or more citations according to on-site data	2022-10-20
IEEEXplore	(”Document Title”:Neuralink) OR (”Publication Title”:Neuralink) OR (”Abstract”:Neuralink)	7	4 with 2 or more citations according to on-site data	2022-10-20
Web of Science	”Neuralink” (Topic)	15	8 with 2 or more citations according to on-site data	2022-10-20
SCOPUS	(TITLE-ABS-KEY (stentrode) OR TITLE-ABS-KEY (”stent electrode”) OR TITLE-ABS-KEY (”stent based electrode”)) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002))	29	9 with 9 or more citations according to on-site data	2022-10-21
IEEEXplore	(”Document Title”:stentrode) OR (”Abstract”:stentrode) OR (”Publication Title”:stentrode) OR (”Document Title”:”stent electrode”) OR (”Publication Title”:”stent electrode”) OR (”Abstract”:”stent electrode”) OR (”Document Title”:”stent based electrode”) OR (”Publication Title”:”stent based electrode”) OR (”Abstract”:”stent based electrode”)	7	1 with 9 or more citations according to on-site data	2022-10-21
Web of Science	stentrode (Topic) or ”stent electrode” (Topic) or ”stent based electrode” (Topic)	22	8 with 9 or more citations according to on-site data	2022-10-21
Google	list of conflict minerals	Unknown, only first page of results were checked.		2023-05-23
Google	lista av konflikt mineraler	Unknown, only first page of results were checked.		2023-05-23

TABLE III
TABLE OF FOUND PARAMETERS FOR EACH PROBE DESIGN

Probe name	**Principle**	**Material**	**Measurement depth**	**Standard number of electrodes**	**Foreign Body Response**	**Heat production**	**Vendor**
Utah Arrays	large 2d array of single channel electrode rods mounted in parallel, meant for insertion at a depth of 1.5mm	p-type silicon with tips of platinum and others, polymide layer and glass insulators	0.5 to 1.5mm	100	very high	0.050°C/mW experimentally when exposed to open air outside the brain, 0.029°C/mW simulated with scalp and cranium	BLACKROCK Cyberkinetics /Microsystems /Neurotech (name has varied over the years)
Michigan Probe	flat spike with electrode ends exposed along the side and/or edge, or jutting out of the end	silicon base, iridium, gold and/or platinum electrode tips), silicon oxide cover	2-15mm	4-256	high	no data found	Neuronexus
Neuralink	a large number of thin threads with incorporated electrode channels, inserted individually by a surgical machine	not publicly known	no data found, but seems flexible	32 per thread	not publicly known	not publicly known	Neuralink
Neural Lace	thin flexible net with electrodes embedded in the structure	chromium, palladium, strands of extracellular matrix, silicon nanowire electrodes	no data found, but seems flexible	depends on lace area	minimal	no data found	no data found
Stentrode	endovascular stent with electrodes embedded in structure	platinum electrode tips, nitinol vascular stent	not applicable	insufficient data found	difficult to compare directly due to unique placement	no data found	Synchron