International Journal of Science Academic Research
Vol. 05, Issue 10, pp.8432-8438, October, 2024
Available online at http://www.scienceijsar.com

ISSN: 2582-6425

Research Article

ADVANCES IN STRETCHABLE BIOELECTRONICS FOR NEURAL SIGNAL MONITORING

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Received 19th August 2024; **Accepted** 27th September 2024; **Published online** 22nd October 2024

Abstract

The brain, as the central organ of the nervous system, regulates various physiological functions through intricate networks of neurons and synapses. Disruptions in these networks lead to neurological and psychiatric disorders, such as Parkinson's disease, Alzheimer's disease, and depression. While conventional rigid sensors like electroencephalography (EEG) and electrocorticography (ECoG) are widely used to monitor neural activity, their rigid structures often impede effective biointegration. Recent advances in nanotechnology and stretchable electronics, particularly functionalized elastomers, offer promising solutions to these limitations. These soft bioelectronics are engineered to conform intimately to the dynamic and curvilinear surfaces of brain tissue, enhancing biocompatibility and ensuring long-term stability. Conductive nanomaterials, used as functional fillers, form percolation networks within elastomer matrices, facilitating efficient signal transmission under mechanical deformation. This approach improves electrical performance while minimizing tissue irritation, closely mimicking the mechanical properties of neural tissue. These innovations enable more precise neural recordings, advancing the early diagnosis and treatment of neurological disorders.

Keywords: Diagnosis, Tool, Monitoring, Neurology, Nanotechnology, Stretchable electronics, Neural signal.

INTRODUCTION

The nervous system orchestrates a wide range of bodily processes through complex patterns of neural activity.(Buckner *et al.,* 2008) At the center of this system, the brain plays a crucial role in regulating emotions, forming memories, and processing sensory input. This is achieved through a complex network of billions of neurons, organized into thousands of subtypes and interconnected by quadrillions of synapses, which collectively form the foundation of brain function. (Melssen, 2015) Disruptions in these neural networks can lead to neurological and psychiatric disorders, such as Parkinson's disease, Alzheimer's disease, and depression, which are increasingly prevalent in aging populations and contribute to the global health concern.(Akiyama *et al.,* 2000; Knopman *et al.,* 2021; Skorvanek & Bhatia, 2017) The growing incidence of brain-related diseases, encompassing neurodegenerative, psychiatric, oncological, neurodevelopmental disorders, and injuries requiring neurorehabilitation, underscores the need for advanced neurotechnologies to monitor brain activity effectively. Neurotechnologies have significantly advanced our understanding of brain function and its relationship to various diseases. Traditional bioelectronic devices, such as electroencephalography (EEG), electrocorticography (ECoG), and intracortical electroencephalography (ICE), have provided invaluable insights into the electrophysiological behavior of the brain. (Byrom *et al.,* 2018) Each of these techniques records neural signals at varying spatial and depth resolutions, contributing to the diagnosis and treatment of neurological conditions. (Fu *et al.,* 2017) Despite these advances, these conventional devices are often constructed using rigid materials such as metals and silicon, which can cause high contact impedance, low signal-to-noise ratios, poor tissue adhesion, immune responses, and scarring due to friction between the device and tissue. (Sunwoo *et al.,* 2020)

These difficulties are largely due to "mechanical mismatches" between the soft, dynamic nature of brain tissues and the rigid, dry inorganic materials used in conventional devices (Hong & Lieber, 2019). The development of intrinsically soft electronic has gained attention as a promising solution for seamless integration with the human body, a concept known as "biointegration." (Lim *et al.,* 2020) Functionalized elastomers are highly suitable for intrinsically soft electronics due to their mechanical properties, which closely resemble the softness of brain tissues. (Shim *et al.,* 2021) These elastomers consist of polymeric networks formed by long, entangled chains that are crosslinked to provide both high stretchability and ultrathin form. Such characteristics enable them to conform closely to the curvilinear, dynamic surfaces of brain tissues. heir electrical properties can be enhanced by incorporating functional fillers, such as conductive nanomaterials, creating conductive pathways within the elastomer matrix. Conductive nanomaterials like metallic nanoparticles or carbon nanotubes can be dispersed within the elastomer precursor, and upon crosslinking, a conductive nanocomposite is formed. This method allows the elastomer to act as a stretchable scaffold that supports the conductive fillers, facilitating efficient electrical signal transmission while maintaining the material's inherent mechanical flexibility (Figure 1).

This review aims to explore the recent developments in functionalized elastomers as key components for intrinsically stretchable electronics, focusing on their materials, mechanical properties, percolation networks, and biocompatibility. These aspects are crucial for bioelectronic devices that are designed to interface seamlessly with neural tissues. By highlighting advancements in the field of neural signal monitoring through EEG, ECoG, and ICE sensors, we will discuss how these innovations contribute to high-resolution neural recording and long-term biointegration.

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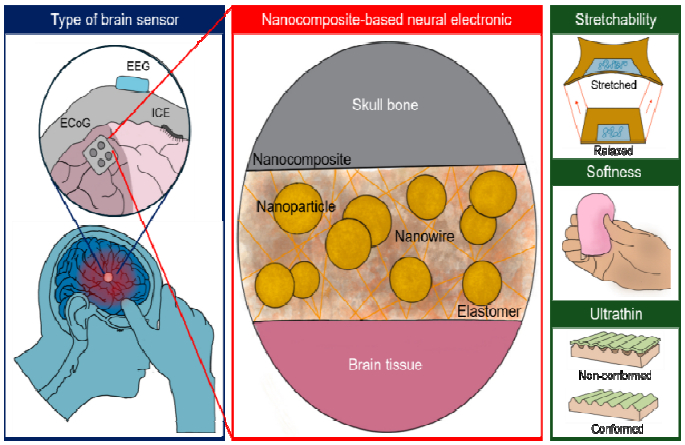

Figure 1.Illustration of neural electronics for brain sensing, including their different sensor types (EEG, ECoG, ICE), material composition (nanoparticles, nanowires, elastomer), and key properties (stretchability, softness, ultrathin conformability)

Brain neural signals

Neural signals recorded from the cerebral cortex can be categorized as field potentials (FP), which include EEG (electroencephalography), ECoG (electrocorticography), and intracortical encephalography (ICE).(Koenig *et al.,* 2005; Sunwoo *et al.,* 2020; Viventi *et al.,* 2011) Each type has distinct characteristics and applications. EEG provides continuous, non-invasive monitoring of brain activity by capturing signals from the scalp with amplitudes ranging from 5–300 μV and frequency bands typically below 100 Hz. However, recording through multiple tissue layers reduces both the spatial resolution (~10 mm) and signal quality, limiting EEG's suitability for high-resolution neuroscience research, where specificity to single neurons is desired. In contrast, invasive neural interfacing methods like ECoG and intracortical probes achieve greater spatiotemporal resolution due to their proximity to brain tissues.(Szostak *et al.,* 2017)ECoG records signals directly from the brain surface, with amplitudes of 0.01–5 mV and frequencies up to 200 Hz, offering a balance between invasiveness and signal quality for clinical applications such as epilepsy monitoring and neuroprosthetics. (Lacour *et al.,* 2016)

ECoG signals provide higher amplitudes and spatial resolution (~1 mm) than EEG and improved signal-to-noise ratios (SNR) due to direct cortical contact. However, ECoGprimarily captures superficial brain activity and is limited in accessing deeper structures or single-neuron spikes. Local field potentials (LFPs), measured by intracortical electrodes, contain signals from both action potentials and other membrane potential fluctuations, offering valuable insight into localized oscillatory brain activity. These signals generally have higher frequency ranges (>300 Hz) and amplitudes (<1 mV) compared to surface recordings. High-pass filtering LFPs isolates neural spikes from nearby neurons, facilitating detailed understanding of specific brain regions' activity. Intracortical electrodes for LFP monitoring, or ICE, are inserted deep within brain tissue, requiring soft, biocompatible, and highly stable probes to minimize inflammatory responses and mechanical damage due to brain micromotions. Advanced micro- and nanoelectrode designs, matching the size and mechanical properties of neurons, enable cellular-level recordings, enhancing both spatial and temporal resolution for in-depth brain research.

Intrinsically stretchable electronics

Soft implantable bioelectronics have garnered significant attention due to their unique capacity to mirror the mechanical properties of biological tissues while maintaining electrical performance akin to conventional rigid devices. These intrinsically soft devices hold great potential for addressing clinical challenges in neuroengineering, where interfacing with the brain requires careful consideration of materials, design, and functionality. The brain's complex and dynamic environment necessitates bioelectronics that can conform to its structures while providing reliable electrical performance. This chapter explores the essential components of intrinsically stretchable electronics, focusing on their materials, mechanical properties, percolation networks, and biocompatibility, which are key to their effective integration with the human body.

MATERIALS

The development of intrinsically soft electronics hinges on choosing materials that can maintain electronic function while accommodating deformation. This section covers two key material classes functional fillers and elastomers that contribute to the mechanical and electrical properties required for high-performance bioelectronics.

Functional fillers

Functional fillers play a crucial role in modifying the mechanical and electrical properties of stretchable electronics. These fillers are typically nanoscale materials (0D, 1D, or 2D), including metal-based nanomaterials (*e.g.*, gold, silver, platinum) and carbon-based nanomaterials (*e.g.*, carbon black, carbon nanotubes (CNTs), graphene). (Figure 2) When incorporated into elastomeric matrices, these fillers form conductive networks, known as percolation networks, which enable efficient charge transport and electrical conduction even under mechanical strain.(Cho *et al.,* 2022) The shape, size, concentration, and distribution of fillers are pivotal factors that determine the network's effectiveness and the overall electrical performance of the nanocomposite.

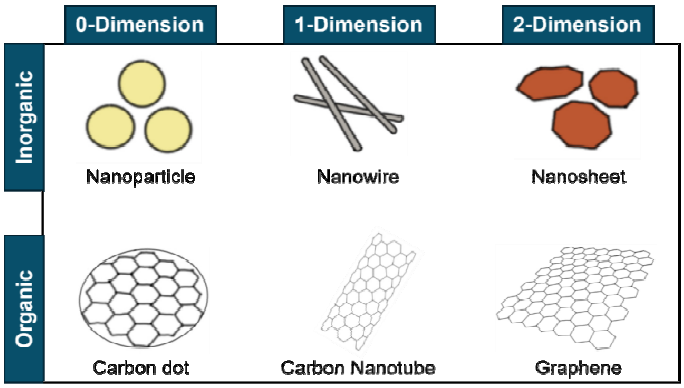

Figure 2. Classification of functional fillers by their dimensions and compositions

Metal-based fillers, which can be synthesized in various forms like nanoparticles (0D), nanowires (1D), and nanoflakes (2D), offer high conductivity but can compromise stretchability if added in excess. Carbon-based fillers, such as CNTs and graphene, provide both flexibility and electrical properties; however, their conductivity is generally lower than that of

metals. Therefore, the use of hybrid fillers, like metal-polymer composites, has emerged to balance mechanical compliance and electrical performance. For instance, gold- or silver-coated nanowires embedded within polymer matrices have shown both high conductivity and flexibility, optimized by surface functionalization to ensure uniform dispersion and adhesion within the elastomer matrix.(Sunwoo *et al.,* 2021). Achieving an optimal balance between electrical conductivity and mechanical flexibility is critical. Excessive filler content can negatively affect crosslinking within the elastomer, resulting in reduced stretchability and increased brittleness.(Li *et al.,* 2007) When combined with elastomers, these fillers facilitate the development of conformal, high-resolution neural interfaces, enhancing precision in recording neural signals and modulation for bioelectronic applications.

Elastomers and their mechanical properties

Elastomers are polymer networks that form the foundation of intrinsically stretchable electronics due to their exceptional elasticity and ability to deform without losing structural integrity. By crosslinking polymer chains, either physically (*via* weak interactions like hydrogen or ionic bonding) or chemically (through stronger covalent bonds), elastomers can be tailored for mechanical properties that align with the requirements of biological tissues.(H. Lim *et al.,* 2020) The density and strength of this crosslinking are critical in determining an elastomer's stretchability and Young's modulus. While denser crosslinking creates stiffer, more durable materials, less extensive crosslinking yields softer, more flexible networks. The mechanical properties of elastomers play a vital role in achieving compatibility with biological tissues. (Figure 3) Unlike traditional rigid materials like metals and silicon, which have elastic moduli over 100 GPa, elastomers exhibit much lower moduli, often as low as 1 kPa.(Shim *et al.,* 2021) This softness closely matches that of neural tissues (0.1 to 10 kPa), ensuring the electronics can conform to the body's dynamic surfaces without inducing tissue strain, inflammation, or scarring, thereby improving biocompatibility. The viscoelastic behavior of elastomers characterized by stress relaxation and energy dissipation allows them to mimic the dynamic mechanical environment of biological tissues, enabling adaptive and long-term performance.

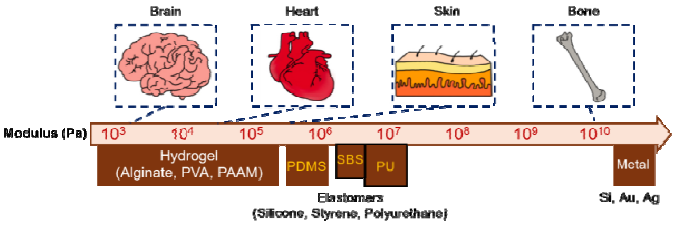

Figure 3. Comparison of Young's modulus (Pa) across different biological tissues (brain, heart, skin, bone) and corresponding materials used in stretchable electronics (hydrogel, elastomers, metals)

Incorporating functional fillers, such as metallic nanomaterials or conductive polymers, into elastomers enhances their mechanical properties and electrical conductivity. This approach enables the creation of highly flexible, conductive devices that maintain their electrical performance even when deformed. Hydrogels, a subset of elastomers with high water content, offer tissue-like properties that enable soft, conformal interfacing with biological tissues.(Gaharwar *et al.,* 2014) Functionalized with conductive fillers like PEDOT or metallic nanoparticles, hydrogels achieve conductivity while maintaining their inherent softness, improving the chronic stability of neural interfaces. The elasticity of elastomers is particularly advantageous for neural applications. They maintain a low Young's modulus and allow for intimate coupling with neural tissues, reducing tissue irritation and foreign body response. (Choi *et al.,* 2019) Surface modifications, such as adhesion-enhancing treatments, further improve biointegration and device longevity. For instance, polydimethylsiloxane (PDMS), styrene-butadiene-styrene (SBS), and polyurethane (PU) are often chosen for intrinsically stretchable bioelectronics due to their stretchability and biocompatibility. Additionally, elastomers are designed to maintain intimate contact with dynamically deformable tissues like skin, muscles, and heart, where strains can range from 10% to 20%. The ability of elastomers to stretch with the tissue ensures their seamless integration and functionality. For certain hydrogels, their modulus can be approximately 1 kPa, matching or falling below that of brain tissue, facilitating their use in sensitive neural applications. By utilizing elastomers with appropriate viscoelastic properties and nonlinear strain-stress relationships, mechanical mismatch between the bioelectronic device and biological tissue can be minimized. Consequently, replacing rigid materials with functionalized elastomers resolves issues related to signal fidelity, long-term biocompatibility, and mechanical mismatch in soft bioelectronics.

Percolation network

Percolation networks within elastomers are critical for achieving electrical conductivity in stretchable electronics. These networks are formed by distributing conductive fillers such as metallic nanowires, nanoparticles, or carbon nanotubes throughout the elastomer matrix, creating interconnected pathways that facilitate electron transport.(G.-H. Lim *et al.,* 2017) The effectiveness of these networks largely depends on achieving an optimal percolation threshold, the critical concentration of fillers required to establish continuous conductive paths. Factors such as the shape, size, and distribution of the fillers play a decisive role in influencing this threshold.(Llerena Zambrano *et al.,* 2021). The shape of the fillers is particularly important for forming a stable percolation network. (**Figure 4**) For example, when 0D microscale fillers like aluminum oxide microparticles are dispersed in the elastomer matrix, they remain isolated and fail to form a network. (Fig. 4 left) However, an equal volume of 1D fillers, such as carbon fibers, is more likely to create interconnected pathways. (Fig. 4 middle) Although a percolation network can eventually form by adding a larger concentration of 0D fillers, their excess disrupts the soft mechanical properties of the elastomer. In contrast, 1D materials effectively form a percolation network while preserving the elastomer's mechanical flexibility and stretchability. The size of the fillers also significantly influences the percolation network.(Wang *et al.,* 2015) Nanoscale fillers, such as silver nanoparticles can form denser and more stable networks compared to microscale fillers like aluminum oxide particles. (Fig. 4 right) This density arises because a higher number of nanoscale fillers are present in the matrix, even at the same volume or weight percent as larger fillers, increasing the likelihood of contact and connectivity. Thus, nanoscale materials are widely preferred as functional fillers to fabricate elastomer composites with optimal conductivity.

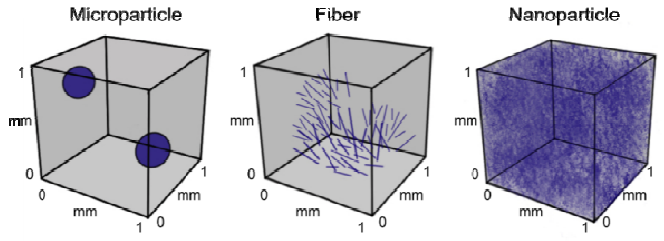

Figure 4. Percolation network of shape and size of fillers

Biocompatibility

Biocompatibility is a fundamental requirement for bioelectronics in neural applications. Stretchable electronics must not only match the mechanical properties of biological tissues but also maintain long-term stability and functionality without triggering adverse biological reactions.(Park *et al.,* 2022) This necessitates the use of non-toxic materials that promote cellular integration, resist biofouling, and remain stable over time. For neural implants, materials like naturally occurring metals (*e.g.*, magnesium, calcium) offer inherent biocompatibility but degrade within the body, limiting their use for chronic applications.(Zhang *et al.,* 2015) In contrast, bioinert metals such as gold and platinum provide long-term durability and stable operation in the brain, although their rigidity requires adaptation into nanostructured forms with polymer substrates to mitigate mechanical mismatch. The integration of nanomaterials, elastomers, and biocompatible design principles has propelled the development of intrinsically stretchable electronics, enabling reliable, minimally invasive neural interfacing. These technologies are poised for applications in both neural signal recording. The use of biocompatible substrates and encapsulation layers comprising elastomers, polymers, or hydrogels further enhances the stability and longevity of bioelectronics by minimizing inflammatory responses and optimizing device performance *in vivo*.

Application

The development of soft, intrinsically stretchable bioelectronic sensors has revolutionized neural recording by providing flexible, biocompatible interfaces that closely conform to biological tissues. This chapter focuses on three primary sensor types EEG, ECoG, and LFP all of which leverage the advantages of stretchable electronics to enhance neural signal acquisition, minimize tissue damage, and improve long-term stability. By integrating soft bioelectronic materials, these sensors achieve high performance and functionality across different levels of neural interfacing.

EEG sensor

EEG sensors are designed to record electrophysiological signals generated by brain activity from the scalp, offering a non-invasive means to monitor neural dynamics. While their on-skin application is a key advantage over other techniques, the recorded signals must pass through multiple tissue layers, leading to low signal amplitudes (5–300 μV) and limited spatiotemporal resolution (~10 mm, ~50 ms). To improve signal quality, electrolytic gels are often applied to minimize impedance and maximize the signal-to-noise ratio (SNR). (Gao *et al.,* 2018) However, the drying of the gel over time reduces its efficacy, necessitating alternative strategies for reliable long-term monitoring. To overcome these limitations, soft, skin-mountable electrodes have been developed that maintain high SNR without the need for gels, providing low impedance and high comfort. A notable example is an electrode developed by(Norton *et al.,* 2015) which uses fractal geometries of ultrathin gold patterned on an elastomeric film. This design enables conformal mounting onto the auricle and mastoid bone, allowing for high-fidelity EEG recordings over an extended period. The electrode's serpentine-shaped, space-filling curves confer an effective modulus of ~130 kPa, ensuring close skin contact while maintaining flexibility. The biocompatibility of materials like silicon, gold, and polyimide used in this system was confirmed through high cell viability (~70%) in cultured keratinocytes, indicating minimal cytotoxicity. The flexibility and softness of this electrode design allowed for effective placement on the curved surface of the ear, minimizing mechanical and electrical noise and avoiding discomfort or skin irritation during long-term wear. Volunteers were able to use the device continuously for over two weeks, successfully recording EEG alpha rhythms in a laboratory setting. Furthermore, the skin-conformal electrodes demonstrated the capability to capture steady-state visually evoked potentials (SSVEP) and P300 waves, enabling brain-computer interface (BCI) applications, such as typing with an accuracy of 84% using an SSVEP-based speller.

EEG sensors can be broadly classified into non-invasive surface EEG (sEEG) and invasive intracranial EEG (iEEG) techniques. Regardless of type, the materials used in these sensors must exhibit non-toxicity and mechanical softness to ensure safe and comfortable interfacing with biological tissues. For instance, stretchable conductive rubbers, like the one developed by(Tybrandt *et al.,* 2018), comprise gold-coated titanium dioxide nanowires (Au–TiO_2 NWs) embedded in polydimethylsiloxane (PDMS). This composite exhibits an initial conductivity of ~16,000 S cm^{-1} at a thickness of 3 μm. Although its resistance increases under strain (up to 100%), its mechanical properties allow it to maintain a conformal fit to neural tissues. Thirty-two-channel neural grid electrodes fabricated from this material were successfully implanted on the somatosensory cortex of rats, recording somatosensory evoked potentials (SSEPs) with low impedance (~10 kΩ at 1 kHz in saline) and stable performance over a period of up to three months. This highlights the potential for creating soft, conformal EEG sensors for extended neural monitoring.

ECoG sensor

Electrocorticography (ECoG) sensors measure electrophysiological signals directly on the dura mater, offering a superior interface with the brain compared to scalp EEG sensors. Because ECoG electrodes make direct contact with the brain surface, they require higher biocompatibility and mechanical softness. This close proximity allows ECoG sensors to achieve higher spatiotemporal resolution (~1 mm, ~30 ms), signal amplitude (10 μV to mV), and signal-to-noise ratios (SNR) than conventional EEG sensors. To address these needs, soft electrodes made of organic, patternable materials have been developed for ECoG monitoring. For example, PEDOT electrodes demonstrated higher SNRs in both cognitive studies and clinical settings (*e.g.*, epileptic seizures), outperforming traditional platinum electrodes by an order of magnitude in terms of noise density across all frequency bands.(Araki, Bongartz, *et al.,* 2020) In tests with human subjects, PEDOT electrodes provided higher-quality ECoG

signals compared to platinum macrodot electrodes, suggesting their promising potential for clinical applications.(Ganji *et al.,* 2018). A notable advancement in ECoG technology is the development of flexible neural interfaces using stretchable, transparent wiring composed of Ag/Au core-shell nanowires. These neural interfaces feature 16 recording channels encapsulated in a 5 μm-thick PPX layer and are treated with an antithrombogenic polymer to inhibit the formation of granulation tissue, which commonly occurs as part of the biological foreign body response.(Araki *et al.,* 2019)The polymer layer softens at body temperature, facilitating stable and transparent contact with the brain surface, while maintaining rigidity during placement. Furthermore, Au nano-plating on Ag nanowires improves ion migration resistance, enhancing the durability of the neural interface in physiological conditions for over five months. Incorporating a polyvinyl alcohol-based gel microelectrode with a low Young's modulus (70–400 kPa) also promotes soft tissue integration and long-term durability.(Duboeuf *et al.,* 2009). Long-term stability and reliability of ECoG signal acquisition were demonstrated through somatosensory evoked potentials (SEPs), a standard method for assessing neural signal consistency after sensory stimulation.(Araki, Uemura, *et al.,* 2020)While SEPs typically attenuate over time due to tissue reaction and device encapsulation, the antithrombogenic-treated neural interfaces maintained high-quality signal acquisition after two months of *in vivo* implantation, effectively preventing the growth of granulation tissue after five months. Furthermore, the transparency of the neural interface enabled the use of optogenetic techniques, allowing optical stimulation of marmoset brain tissue and recording of neural responses to blue laser or LED light with low noise, demonstrating the versatile functionality of the interface for both electrical and optical neural interfacing. Additionally, recent innovations include intrinsically stretchable neurochemical biosensors like NeuroString, which integrate laser-induced graphene nanofiber networks within an elastomer matrix.(Li *et al.,* 2022) These sensors can detect real-time dynamics of multiple neurotransmitters in the brain and gut, combining flexibility and stretchability akin to biological tissues while maintaining the electrochemical properties of nanomaterials. Such properties of graphene allow dual-mode detection for electrophysiological and electrochemical measurements, offering multifunctional capabilities for *in vivo* neural monitoring. These advancements in ECoG technology underline the potential of soft, biocompatible sensors for precise, long-term neural interfacing and signal acquisition.

LFP sensor

Local field potential (LFP) sensors, which record intracortical electrophysiological signals, offer significant advantages over EEG and ECoG techniques due to their higher signal-to-noise ratio (SNR) and more localized information, with spatiotemporal resolutions around ~0.1 mm and ~30 ms . However, the invasive nature of LFP recording limits its widespread application outside clinical contexts . Additionally, the intracortical environment characterized by its soft, ion-rich, and fluidic nature poses challenges for the long-term use of conventional rigid bioelectronics. Such bioelectronics often suffer from mechanical, chemical, and electrical mismatches with brain tissue, which can lead to reduced functionality and adverse biological responses over time. Even advanced materials have struggled to meet the stringent criteria required for LFP sensors. Thin metal films, for example, offer high conductivity and can be fabricated into high-resolution electrodes(Lee *et al.,* 2019; Sunwoo *et al.,* 2019); however, their chemical and electrical incompatibility with the intracortical milieu can limit their effectiveness.(Szostak *et al.,* 2017)On the other hand, conductive polymers and hydrogels present a mechanical and chemical match to the brain but typically exhibit low conductivity, compromising signal quality. To address these challenges, composite materials have been developed, combining the advantages of different materials to minimize mismatches without compromising functionality . For instance, Nam et al. fabricated an injectable LFP electrode composed of a composite material, blending a supramolecular β-peptide-based hydrogel with conductive carbon nanotubes (CNTs).(Nam *et al.,* 2020) This βVhex/CNT/hydrogel composite possesses a low modulus (~1,500 Pa), similar to that of brain tissue, thus minimizing mechanical damage upon implantation . The composite provides a unique solution to the inherent design dilemma of LFP sensors: the need for stiffness during initial insertion into the cortex and softness to avoid long-term mechanical damage. The hydrogel composite retains brain-like softness but can be implanted *via* syringe injection, enabling targeted placement in the cortex without significant disruption.

In their study, Nam et al. successfully implanted the injectable LFP electrode into the layer II/III of the somatosensory cortex in a chronic epileptic mouse model. The composite's large surface area, combined with the ionic nature of the hydrogel and high conductivity of CNTs, significantly reduced impedance, enhancing the quality of LFP recordings. During epileptic events, the sensor captured beta and gamma band signals that were 3-fold and 2.4-fold stronger, respectively, compared to those recorded with a standard hydrogel or bare electrode. Despite its flexibility, the hydrogel composite demonstrated minimal degradation, attributed to the high stability of the β-peptide, and did not interfere with cerebral blood flow. Histological analysis further demonstrated that the hydrogel-based LFP electrode induced significantly lower inflammatory responses over a 12-week implantation period compared to traditional metal electrodes, highlighting its potential for stable, long-term intracortical recording with reduced biological reactivity.

Conclusion

The development of intrinsically stretchable electronics marks a significant breakthrough in neural interfacing technologies, offering enhanced stretchability, softness, and conformal contact as well as stability over conventional rigid devices. Central to these advances is the use of functionalized elastomers, which mimic the mechanical properties of soft and curvilinear brain tissues, enabling seamless integration. By incorporating conductive fillers such as inorganic and organic nanomaterials, elastomers form percolation networks that facilitate charge transport while retaining mechanical stretchability. Fine-tuning these networks through careful control of filler concentration and distribution optimizes both conductivity and stretchability, allowing for efficient neural signal acquisition without compromising the device's softness and conformability. The mechanical characteristics of elastomers, particularly their viscoelasticity, play a pivotal role in enhancing neural signal fidelity and device performance. Their ability to match the low Young's modulus of neural tissues ensures minimal tissue damage and inflammation,

supporting long-term stability *in vivo*. Additionally, hybrid composites, such as gold-coated nanowires embedded in elastomer matrices, balance electrical performance and mechanical compliance, leading to more precise neural recordings at high spatial and temporal resolution. Applications of these advances in EEG, ECoG, and LFP sensors have demonstrated the potential for high-quality neural monitoring. For example, ultrathin gold electrodes for EEG provide improved signal-to-noise ratios (SNR), while PEDOT-based ECoG sensors offer direct cortical recording with higher resolution. Intracortical LFP sensors utilizing soft, injectable hydrogels closely mimic brain tissue properties, enabling cellular-level recording and further expanding the functionality of neural interfaces. Looking forward, the intersection of materials science, bioengineering, and neuroscience will continue to drive advancements in functionalized elastomers and soft bioelectronics. Future efforts will focus on enhancing biocompatibility, stability, and multifunctionality of neural devices through innovative filler integration and polymer matrix designs. The overarching goal is to minimize immune responses and mechanical mismatches for chronic implantation while achieving precise neural signal acquisition and modulation. As these technologies evolve, they will play an increasingly crucial role in neuroprosthetics, brain-computer interfaces (BCIs), and therapeutic monitoring, ultimately bridging the gap between engineered devices and biological systems for improved brain health and neurorehabilitation.

Acknowledgements: I would like to thank Calvin Cho for his guidance and encouragement during process of this review.

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