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Development and Innovative Applications of Tools for Monitoring Neuronal Electrical Activity

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Abstract. Neuronal electrical activity provides the most direct dynamic readout of excitability, synaptic transmission, circuit coordination, and information processing in the nervous system. Monitoring tools have evolved from intracellular and patch-clamp recordings that resolve ion-channel and membrane currents to high-density extracellular arrays, flexible neural interfaces, optical activity indicators, wireless implants, and artificial intelligence-assisted decoding systems. Each modality captures a different level of neural organization. Patch-clamp recording provides high biophysical precision at the single-cell scale, microelectrode arrays and silicon probes enable population recordings across networks, electroencephalography and functional magnetic resonance imaging support noninvasive human studies, and optical sensors map calcium, voltage, or neurochemical dynamics with cellular or subcellular resolution. Recent advances in ultraflexible electrodes, mesh electronics, genetically encoded indicators, nanomaterials, closed-loop bioelectronics, and machine learning have shifted neural monitoring from episodic measurement toward chronic, multimodal, and intervention-linked systems. This review summarizes traditional and emerging tools for monitoring neuronal electrical activity, analyzes multimodal integration strategies, and discusses applications in disease mechanism research, brain-computer interfaces, neuromodulation, brain-inspired intelligence, and neural engineering. Translation will depend on long-term biocompatibility, stable signal quality, interpretable computational models, and standards that connect device performance with biological validity.

Keywords: Neuronal electrical activity, Patch clamp, Microelectrode array, Neuropixels, Genetically encoded indicators

1. Introduction

Electrical activity is the operational language of the nervous system. Action potentials, synaptic currents, local field potentials, oscillations, and large-scale network rhythms link ion-channel biophysics with perception, cognition, movement, autonomic regulation, and behavior.

Tools monitoring these signals determine the spatial and temporal scale at which neural function can be studied. A single whole-cell recording can resolve subthreshold membrane dynamics and synaptic conductances, whereas population recordings capture ensemble coordination, synchrony, and state transitions. As for noninvasive human techniques,they extend monitoring to clinical and

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cognitive contexts, although they measure summed or hemodynamic signals rather than single-neuron currents. The history of neuronal activity monitoring is trade-offs among resolution, invasiveness, stability, throughput, and interpretability [1, 2].

Contemporary neuroscience requires more tools that bridge scales than before. Disease mechanisms often emerge from interactions between ion channels, synapses, glial regulation, vascular coupling, circuit oscillations, and behavior. Brain-computer interfaces require stable recordings from many neurons over long periods and computational models that can decode intended movement or speech. The requirement for quantitative descriptions of how biological networks process information and adapt to stimulation in neural engineering and brain-inspired computing has pushed monitoring technologies beyond conventional electrodes toward high-density silicon probes, soft implantable electronics, optical voltage and calcium sensors, nanoscale bioelectronic materials, wireless platforms, and artificial intelligence-based signal processing [3-5].

This review discusses the development and innovative applications of neuronal electrical activity monitoring tools. The article follows a technical-to-translational structure, beginning with patch clamp, multielectrode arrays, electroencephalography, and functional magnetic resonance imaging, then moving to high-density electrodes, flexible interfaces, optical activity imaging, nanomaterials, multimodal systems, wireless implants, and computational decoding.Each method provides a solution to a different biological question.

A rigorous monitoring strategy is selected by matching the signal source, anatomical target, timescale, perturbation tolerance, and computational analysis to the scientific or clinical objective.

2. Traditional technologies for monitoring neuronal electrical activity

2.1. Patch-clamp techniques

Patch-clamp recording remains the reference method for measuring membrane currents and excitability with high temporal and amplitude resolution. The discovery that single-channel currents could be recorded from biological membranes established a direct experimental route to ion-channel biophysics [1]. Subsequent improvements in gigaseal formation, low-noise amplifiers, and cell-attached, inside-out, outside-out, whole-cell, and perforated-patch configurations transformed the method into a central tool for cellular electrophysiology [6]. Current-clamp recordings quantify resting potential, firing threshold, input resistance, adaptation, and action-potential waveform. Voltage-clamp recordings measure synaptic currents and isolate ionic conductances under defined command potentials.

The major strength of patch clamp is mechanistic precision. It can assign changes in neuronal excitability to sodium, potassium, calcium, chloride, ligand-gated, or synaptic currents and can test drug effects with direct control of voltage or intracellular solution. The method also supports paired recordings, dynamic clamp, automated planar patch systems, and recordings from acute slices, cultured neurons, organoids, and in vivo preparations. Its limitations are low throughput, technical difficulty, cellular disturbance after whole-cell access, and limited coverage of distributed circuits. Patch clamp functions best as a biophysical anchor for interpreting signals acquired by higher throughput and less invasive technologies.

2.2. Multielectrode arrays

Multielectrode arrays record extracellular voltage changes from many sites simultaneously. Planar arrays are widely used for cultured neuronal networks, brain slices, retinal preparations, cardiac

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tissue, and disease models derived from induced pluripotent stem cells.

They capture spike timing, burst structure, synchrony, propagation, and the maturation of network without rupturing cell membranes. Three-dimensional and high-density arrays improve cell-electrode coupling and spatial sampling, while complementary stimulation electrodes allow perturbation of network activity.In my opinion MEA recordings have already become a standard platform for neurotoxicity testing, seizure-like activity analysis, developmental neurobiology, and pharmacological screening [7].

Extracellular arrays trade intracellular resolution for parallel sampling. They infer action potentials from local field changes rather than directly measuring membrane potential, and signal amplitude depends on electrode impedance, distance to the neuron, tissue-electrode interface, and spike-sorting quality. High-density complementary metal-oxide-semiconductor arrays reduce these limitations by increasing recording sites and improving spatial localization. The same design logic shaped in vivo silicon probes. Neuropixels probes integrate hundreds to thousands of recording channels on a slender shank, enabling simultaneous recordings across multiple brain regions in behaving animals .In addition, Neuropixels 2.0 further miniaturized the probe and improved chronic stability, supporting repeated recordings from neuronal populations over longer time windows [8]. The densely arranged recording sites along the slender probe shank enable spatially resolved sampling of extracellular neural activity across extended brain regions (Figure 1).

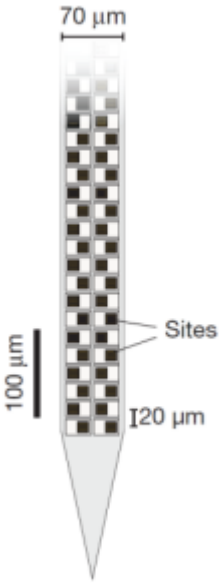

Figure 1. High-density recording-site layout at the tip of the Neuropixels neural probe [3]

2.3. Electroencephalography and functional magnetic resonance imaging

Electroencephalography records scalp voltage fluctuations generated mainly by synchronized postsynaptic currents in aligned cortical pyramidal neurons. It provides millisecond temporal resolution and supports analyses of oscillatory power, event-related potentials, phase coupling, microstates, seizure dynamics, sleep stages, and cognitive task responses. EEG is noninvasive, portable, and clinically established, but spatial resolution is limited by volume conduction, skull conductivity, reference choice, and inverse problem uncertainty. Intracranial EEG and electrocorticography improve spatial specificity, although they require invasive access and are used mainly in clinical or implant settings [2, 9].

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Functional magnetic resonance imaging measures hemodynamic consequences of neural activity rather than electrical signals. Blood-oxygen-level dependent contrast offers millimeter-scale coverage across the whole brain and can identify functional networks, sensory maps, disease-associated connectivity changes, and task-related activation. The temporal resolution is slower than electrophysiology, and neurovascular coupling can vary with development, disease, medication, and vascular state. EEG and fMRI are complementary. EEG resolves rapid electrical dynamics, whereas fMRI localizes distributed network activity and subcortical involvement. The two modalities are often combined to relate oscillations, epileptic discharges, and cognitive rhythms to brain-wide hemodynamic responses [10].

Signal interpretation in noninvasive monitoring depends heavily on preprocessing and model choice. EEG analysis requires control of ocular, muscle, cardiac, motion, and line-noise artifacts, and results can change with filtering, referencing, epoch selection, and source-estimation assumptions. Functional MRI requires motion correction, physiological noise modeling, spatial normalization, and careful treatment of vascular confounds. Wearable and ear-centered EEG systems extend monitoring to mobile and long-duration settings, but these devices intensify the need for transparent quality metrics because electrode contact, sweating, movement, and environmental noise can dominate the recorded signal [11].

3. Emerging technologies for monitoring neuronal electrical activity

3.1. High-density neural electrodes and flexible neural interfaces

High-density electrodes have altered the scale of extracellular monitoring. Silicon probes with integrated recording electronics can sample hundreds of neurons across cortical and subcortical structures during behavior, while improved spike sorting links extracellular waveforms to putative single units.Population geometry, cell-type-related firing patterns, and interactions among brain regions were revealed in the dense recordings. The remaining technical problems such as tissue displacement during implantation, inflammatory encapsulation, micromotion, channel failure, data bandwidth, and maintaining unit identity across days. Stable long-term recordings require mechanical and biological compatibility in addition to channel count [3, 8]. According to the figure, Neuropixels 2.0 has demonstrated stable population-level recordings over extended implantation periods, with persistent neural activity detectable across cortical and subcortical structures (Figure 2).

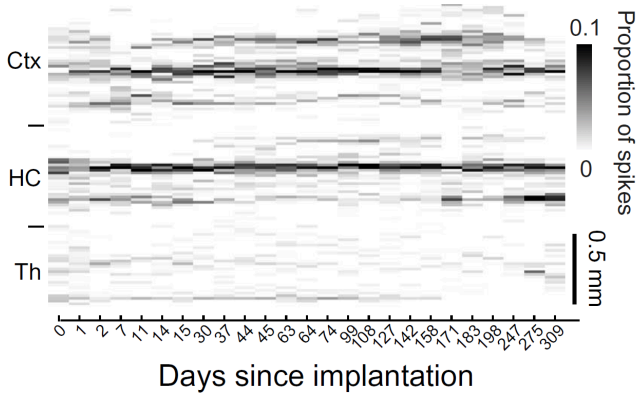

Figure 2. Long-term stability of Neuropixels 2.0 recordings across multiple brain regions [8]

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Flexible neural interfaces address the mechanical mismatch between rigid electronics and soft neural tissue.Foreign-body response was reduced by mesh electronics, ultraflexible nanoelectronic probes, stretchable electrodes, and polymer-based arrays matching tissue mechanics more closely. Syringe-injectable electronics demonstrated that macroporous mesh structures can be delivered into brain tissue and integrate with neural networks. Chronic single-neuron mapping with mesh electronics and glial-scar-free integration with ultraflexible probes showed that device geometry and bending stiffness strongly influence long-term signal quality [4, 5]. These platforms extend monitoring from short experimental sessions toward longitudinal studies of development, plasticity, disease progression, and recovery.

3.2. Optical monitoring of neural activity

Optical monitoring converts neural activity into fluorescence or luminescence signals. Calcium imaging is widely used due to action potentials and synaptic input elevate intracellular calcium, then genetically encoded calcium indicators such as GCaMP permit cell-type-specific, chronic, and population-scale imaging. GCaMP6 improved sensitivity and kinetics enough to support reliable detection of activity in many neuronal systems. Newer indicator engineering has continued to improve brightness, affinity, kinetics, spectral diversity, and subcellular targeting [12, 13]. Although calcium signals remain indirect and can be distorted by buffering, saturation, dendritic compartmentalization, and nonlinear coupling between spikes and calcium influx,two-photon microscopy, miniature microscopes, light-sheet imaging, and fiber photometry allow activity monitoring in behaving animals.

Voltage imaging provides us with a more direct optical readout of membrane potential. Genetically encoded voltage indicators can report subthreshold depolarization, action potentials, and dendritic events, but they require high photon flux, fast imaging, and careful control of phototoxicity and signal-to-noise ratio. Chemically synthesized voltage dyes and hybrid genetically targetable sensors can provide faster kinetics, whereas genetically encoded indicators support cell-type targeting and chronic expression. Reviews of genetically encoded sensors indicates that optical monitoring now extends beyond calcium and voltage to neurotransmitters, neuromodulators, and receptor conformational states [14]. The technical direction is integration of faster indicators with imaging systems that can record large fields of view without losing single-cell or subcellular temporal precision.

3.3. Nanomaterials and intelligent bioelectronic neural sensors

Nanomaterials provide new interfaces between ionic biological signals and electronic conductors. Graphene, carbon nanotubes, conducting polymers, gold nanostructures, nanowires, and hydrogel composites can reduce impedance, increase effective surface area, improve charge injection, and support softer tissue interfaces. Conducting polymers such as PEDOT-based materials are used to improve neural electrode performance and have been reviewed as components of brain-machine interfaces [15]. Organic electrochemical transistors amplify ionic-to-electronic signals at the material interface, allowing sensitive detection of local field potentials and biochemical changes. Nanostructured coatings can also support combined recording, stimulation, drug delivery, or biosensing.

Intelligent bioelectronic sensors combine materials, electronics, and computation. Local preprocessing, artifact rejection, adaptive filtering, feature extraction, and on-device classification reduce data load and enable closed-loop operation. Such systems are relevant when neural signals

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must be monitored continuously in freely moving animals or patients. Sensor intelligence does not eliminate the need for biological validation. Algorithms can amplify systematic artifacts if training data do not represent movement, glial response, electrode drift, or disease state. Reliable smart neural sensors require co-design of materials, recording electronics, stimulation hardware, power management, and signal models.

4. Multimodal technologies for monitoring neuronal electrical activity

4.1. Combined electrophysiological and optical imaging monitoring

Combined electrophysiology and optical imaging links electrical precision with spatial and molecular specificity. Patch clamp can calibrate calcium or voltage indicators at the single-cell level, while extracellular recordings can be aligned with two-photon imaging to connect spikes, local field potentials, calcium dynamics, and circuit state. Simultaneous optogenetic stimulation and electrophysiological recording allow causal testing of cell types and pathways, although optical artifacts and stimulation-induced heating must be controlled. In epilepsy, sensory processing, learning, and sleep research, combined electrical and optical approaches help distinguish whether a network event arises from cellular excitability, synaptic recruitment, neuromodulation, or circuit synchronization [16].

Multimodal monitoring also improves interpretation of optical signals. Calcium transients often reflect a mixture of action potentials, dendritic input, and intracellular signaling. Electrophysiological calibration constrains spike inference and separates neuronal firing from movement or vascular artifacts. Conversely, optical methods identify cell types and anatomical compartments that extracellular electrodes cannot resolve easily. The strongest designs use each modality to correct the weaknesses of the other rather than treating multimodal data as a simple accumulation of channels.

4.2. Combined monitoring of neural signals and artificial intelligence

Artificial intelligence has become central to neural monitoring because modern recordings produce high-dimensional, nonstationary data. Machine learning supports spike sorting, artifact rejection, source localization, sleep staging, seizure detection, behavioral state classification, and brain-computer interface decoding. Deep learning can model nonlinear relationships between population activity and movement, speech, or cognitive state. Brain-to-text systems based on attempted handwriting and high-performance speech neuroprostheses illustrate how neural recordings, recurrent or sequence models, and language constraints can convert cortical activity into communication [17].

The use of artificial intelligence changes the evidentiary standard for monitoring tools. Performance metrics must be linked to biological interpretability, stability across sessions, calibration burden, and failure modes. A decoder that works within one recording day may fail after electrode drift, tissue response, medication changes, or altered behavior. Transparent validation across subjects and time is needed for clinical and engineering applications. Hybrid models that combine neural dynamics, anatomical constraints, and data-driven learning may provide better generalization than purely black-box classifiers.

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4.3. Implantable and wireless neural monitoring systems

Implantable and wireless monitoring systems extend neural recordings beyond constrained laboratory settings. Wireless headstages, battery-free photometry devices, fully implantable stimulators, and closed-loop neuromodulation systems reduce cable-related stress, movement artifacts, and infection risk. Battery-free subdermally implantable photometry systems have enabled chronic recordings of neural dynamics in freely moving animals [18]. Soft, wireless, and subdermally implantable tools are being developed to combine recording, stimulation, and behavioral compatibility [19].

Wireless implants must solve power transfer, heat dissipation, data compression, encapsulation, telemetry reliability, and surgical safety. Closed-loop systems add latency constraints because detection, decision, and stimulation must occur within a physiologically relevant time window. These platforms are particularly relevant to epilepsy, Parkinson's disease, chronic pain, sleep disorders, and neuropsychiatric stimulation. Their development shifts monitoring from passive observation toward adaptive intervention, where signal quality, algorithmic decision-making, and stimulation safety become a single regulatory and engineering problem.

5. Innovative applications of neuronal electrical activity monitoring tools

5.1. Applications in mechanistic studies of neurological diseases

Monitoring tools are central to disease mechanism research because many neurological disorders involve abnormal excitability and network coordination. Patch clamp identifies channel dysfunction, synaptic imbalance, and altered intrinsic excitability in epilepsy, autism spectrum models, neurodegeneration, pain, and ischemic injury. MEA recordings detect hyperexcitability, burst synchronization, and developmental network defects in cultured neurons and organoids. EEG and intracranial recordings define seizure onset zones, sleep abnormalities, encephalopathy, and large-scale oscillatory biomarkers. High-density probes and optical imaging reveal how local microcircuits and distributed ensembles change during disease progression, compensation, and treatment.

Patient-derived induced pluripotent stem cell neurons and brain organoids have increased the demand for scalable electrical monitoring. MEA platforms can compare disease-associated genotypes, drug effects, and network maturation across many cultures, while patch clamp provides cellular validation. In vivo, chronic flexible probes can track the same region during degeneration, recovery, or therapeutic intervention. Disease research benefits most when monitoring is paired with molecular profiling, imaging, behavioral readouts, and perturbation, because electrical abnormalities alone do not specify the cellular mechanism.

5.2. Applications in brain-computer interfaces and neuromodulation

Brain-computer interfaces depend on stable conversion of neural activity into control signals. Intracortical microelectrodes provide high bandwidth for motor intention, handwriting, and speech decoding, whereas EEG-based systems offer noninvasive access with lower spatial specificity. Recent intracortical BCIs have enabled rapid text generation from attempted handwriting, with a representative system reaching approximately 90 characters per minute and demonstrating the potential of neural population decoding for high-bandwidth communication (Figure 3) [17].

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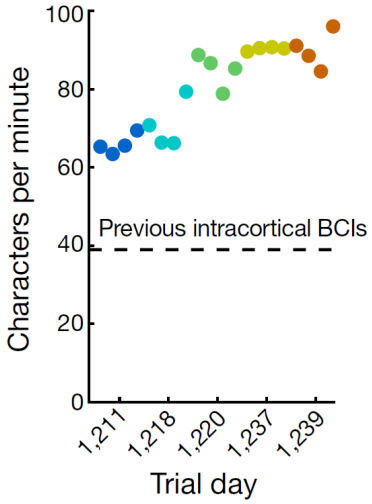

Figure 3. High-rate text communication achieved using an intracortical handwriting brain-computer interface [17]

Neuromodulation uses monitoring not only for readout but also for control. Closed-loop deep brain stimulation, responsive neurostimulation, vagus nerve stimulation, and cortical stimulation rely on biomarkers such as beta oscillations, epileptiform discharges, or state-dependent activity patterns. Monitoring tools must separate pathological activity from movement artifacts and physiological state transitions. Flexible interfaces, wireless telemetry, and on-device algorithms can reduce the gap between laboratory discovery and wearable or implantable clinical systems.

5.3. Applications in brain-inspired intelligence and neural engineering

Brain-inspired intelligence and neural engineering require quantitative descriptions of biological computation. High-density recordings reveal population dynamics, dimensionality, representational drift, and low-dimensional manifolds during behavior. Optical imaging connects cellular identity and anatomical structure with activity patterns. MEA-based cultures and organoids can be used as living networks for studying plasticity, reservoir-like computation, and adaptive stimulation. These applications rely on monitoring tools that can measure activity over long times without destroying the network being studied.

Neural engineering also uses monitoring tools as design feedback. Bioelectronic materials are evaluated by impedance, noise, stimulation threshold, tissue response, and recording stability. Algorithms are tested by their ability to decode behavior, predict state transitions, or identify causal circuit nodes. The next generation of neural monitoring will likely combine soft materials, dense channels, optical or chemical specificity, wireless telemetry, and adaptive computation. The practical value of such systems will depend on whether they make neural activity more interpretable and controllable, not only more abundant.

6. Conclusions and outlook

Tools for monitoring neuronal electrical activity have expanded from single-channel and whole-cell recordings to high-density probes, flexible interfaces, optical sensors, nanomaterial-based bioelectronics, wireless implants, and artificial intelligence-assisted platforms. Patch clamp defines cellular mechanisms, MEAs and silicon probes quantify network and population dynamics, EEG

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and fMRI support human-scale monitoring, and optical indicators add molecular and cellular specificity. No single method covers all relevant scales. Progress in the field comes from matching monitoring modality to biological question and from integrating signals across levels of organization.

Several technical issues remain decisive. Chronic interfaces must reduce tissue response and preserve unit stability. Optical systems need faster indicators, lower phototoxicity, and better access to deep structures. Wireless implants require safe power transfer, reliable telemetry, and low-latency closed-loop control. Artificial intelligence models must remain valid across sessions, subjects, disease states, and device drift. Standards for reporting signal quality, biological validation, artifact rejection, and long-term stability would make results more comparable across laboratories. Neuronal activity monitoring is moving toward integrated systems in which materials, sensors, computation, and intervention are designed together around specific mechanisms and clinical objectives.

References

[1] Neher, E., & Sakmann, B. (1976). Single-channel currents recorded from membrane of denervated frog muscle fibres. *Nature, 260*(5554), 799–802.

[2] Buzsáki, G., Anastassiou, C. A., & Koch, C. (2012). The origin of extracellular fields and currents--EEG, ECoG, LFP and spikes. *Nature Reviews Neuroscience, 13*(6), 407–420.

[3] Jun, J. J., Steinmetz, N. A., Siegle, J. H., et al. (2017). Fully integrated silicon probes for high-density recording of neural activity. *Nature, 551*(7679), 232–236.

[4] Fu, T. M., Hong, G., Zhou, T., Schuhmann, T. G., Viveros, R. D., & Lieber, C. M. (2016). Stable long-term chronic brain mapping at the single-neuron level. *Nature Methods, 13*(10), 875–882.

[5] Luan, L., Wei, X., Zhao, Z., et al. (2017). Ultraflexible nanoelectronic probes form reliable, glial scar-free neural integration. *Science Advances, 3*(2), e1601966.

[6] Hamill, O. P., Marty, A., Neher, E., Sakmann, B., & Sigworth, F. J. (1981). Improved patch-clamp techniques for high-resolution current recording from cells and cell-free membrane patches. *Pflugers Arch, 391*(2), 85-100.

[7] Obien, M. E., Deligkaris, K., Bullmann, T., Bakkum, D. J., & Frey, U. (2014). Revealing neuronal function through microelectrode array recordings. *Front Neurosci, 8*, 423.

[8] Steinmetz, N. A., Aydin, C., Lebedeva, A., et al. (2021). Neuropixels 2.0: A miniaturized high-density probe for stable, long-term brain recordings. *Science, 372*(6539).

[9] Ismail, L. E., & Karwowski, W. (2020). Applications of EEG indices for the quantification of human cognitive performance: A systematic review and bibliometric analysis. *PLoS One, 15*(12), e0242857.

[10] Logothetis, N. K. (2008). What we can do and what we cannot do with fMRI. *Nature, 453*(7197), 869-78.

[11] Kaongoen, N., Choi, J., Woo Choi, J., et al. (2023). The future of wearable EEG: A review of ear-EEG technology and its applications. *Journal of Neural Engineering, 20*(5).

[12] Shen, Y., Nasu, Y., Shkolnikov, I., Kim, A., & Campbell, R. E. (2020). Engineering genetically encoded fluorescent indicators for imaging of neuronal activity: Progress and prospects. *Neuroscience Research, 152*, 3-14.

[13] Inoue, M. (2021). Genetically encoded calcium indicators to probe complex brain circuit dynamics in vivo. *Neuroscience Research, 169*, 2-8.

[14] Dong, C., Zheng, Y., Long-Iyer, K., Wright, E. C., Li, Y., & Tian, L. (2022). Fluorescence imaging of neural activity, neurochemical dynamics, and drug-specific receptor conformation with genetically encoded sensors. *Annual Review of Neuroscience, 45*, 273-94.

[15] Ziai, Y., Zargarian, S. S., Rinoldi, C., et al. (2023). Conducting polymer-based nanostructured materials for brain-machine interfaces. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 15*(5), e1895.

[16] Emiliani, V., Entcheva, E., Hedrich, R., et al. (2022). Optogenetics for light control of biological systems. *Nature Reviews Methods Primers, 2*.

[17] Willett, F. R., Avansino, D. T., Hochberg, L. R., Henderson, J. M., & Shenoy, K. V. (2021). High-performance brain-to-text communication via handwriting. *Nature, 593*(7858), 249–54.

[18] Burton, A., Obaid, S. N., Vázquez-Guardado, A., et al. (2020). Wireless, battery-free subdermally implantable photometry systems for chronic recording of neural dynamics. *Proceedings of the National Academy of Sciences of the United States of America, 117*(6), 2835–45.

DOI: 10.54254/2753-8818/2026.ES38045

[19] Cai, L., & Gutruf, P. (2021). Soft, wireless and subdermally implantable recording and neuromodulation tools. *Journal of Neural Engineering, 18*(4).