An Exhaustive Review of Electrophysiological Brain Interface Technologies: Electrodes, Placement, and Invasiveness

Introduction

Purpose and Scope

This report provides a comprehensive, expert-level analysis of the technologies and methodologies used for recording electroencephalographic (EEG) signals. It covers the full spectrum of the field, from the fundamental electrode-tissue interface to the standardized systems for electrode placement and the varying levels of procedural invasiveness. The primary objective is to synthesize a vast body of clinical, research, and technical information into a single, cohesive document intended for an audience of researchers, clinicians, and engineers in neuroscience and biomedical engineering. The analysis will delve into the materials, form factors, and electronic principles of different electrodes; the historical development and practical application of international placement standards; and the critical trade-offs associated with non-invasive, semi-invasive, and fully invasive recording modalities.

Historical Context

The field of electroencephalography began in 1924 when German psychiatrist Hans Berger first recorded the electrical activity of the human brain using simple silver foil electrodes placed on the scalp.[1] This pioneering work opened a window into the functioning brain, revealing the faint electrical fields generated by the synchronized activity of millions of underlying neurons.[2] From its inception, the core challenge of

EEG has been to accurately capture these minuscule electrical signals, which are significantly attenuated and distorted as they propagate through the various layers of brain tissue, cerebrospinal fluid, bone, and scalp.[2] The subsequent century of innovation has been characterized by a continuous and evolving effort to improve the fidelity of these recordings while simultaneously enhancing their usability and accessibility. This evolution prompted the first International EEG congress in 1947 to recognize the urgent need for standardized methods to ensure that recordings could be reliably reproduced and compared across different laboratories and subjects, a foundational principle for scientific and clinical validity.[2]

Core Concepts

Electroencephalography is the neurophysiological measurement of voltage fluctuations resulting from ionic current within the neurons of the brain.[2] While the electrical signal from a single neuron is far too small to be detected from the scalp, the synchronous firing of large populations of neurons, particularly the pyramidal cells of the cerebral cortex, generates a macroscopic electrical field that becomes measurable.[2] The technologies discussed in this report represent different strategies to solve the fundamental problem of detecting these signals. The choice of technology—from the type of electrode used, to its placement on the head, to the degree of surgical intervention—is dictated by a complex interplay between the desired signal quality, the specific clinical or research question being addressed, and the acceptable level of risk and cost. This report will systematically deconstruct these factors to provide a clear and nuanced understanding of the current state and future direction of electrophysiological brain interface technologies.

Part I: The Electrode-Tissue Interface: A Foundational Analysis

The most fundamental component of any EEG system is the electrode, the transducer responsible for converting the ionic currents of the body into the electronic currents measured by an amplifier. The design, material composition, and application method of an electrode profoundly influence the quality, stability, and usability of the resulting data. This section provides a foundational analysis of electrode technologies, exploring how different approaches have evolved to navigate the inherent trade-offs between signal fidelity and practical application.

Section 1.1: Classification of EEG Electrodes by Application Method

1.1.1 Wet Electrodes: The Clinical Gold Standard

For decades, wet electrodes have been the benchmark against which all other non-invasive EEG technologies are measured, earning them the title of the "gold standard" in both clinical and research settings.[1]

Description and Materials: The archetypal wet electrode is a small cup or disc, traditionally manufactured from Silver (Ag) coated with a layer of Silver Chloride (AgCl).[1] The Ag/AgCl composition is not arbitrary; it is a critical element for creating a stable, non-polarizable electrode. Because AgCl is a slightly soluble salt, it maintains a stable equilibrium of chloride ions at the electrode surface, which facilitates the efficient and low-noise transduction of ionic currents from the body into electronic current in the electrode wire.[8]

Mechanism of Action: The defining feature of a wet electrode is its reliance on a conductive medium to form a stable electrical bridge between the electrode and the scalp. This medium is typically an electrolytic gel or paste (such as "ELGEL-P") that is rich in chloride ions.[1] The gel is applied through a central hole in the cup electrode, filling the space between the metal and the skin. This serves two purposes: it lowers the skin-electrode impedance, which is the opposition to current flow, and it ensures a continuous, stable conductive pathway. To further reduce impedance, the scalp is often prepared beforehand with a light abrasive scrub to remove dead skin cells and oils.[1] This meticulous preparation is what allows wet electrodes to achieve the very low impedance values necessary for high-fidelity recordings.[7]

Performance and Signal Quality: The primary advantage of wet electrodes is their superior signal quality. The low-impedance interface they create results in a high signal-to-noise ratio (SNR), meaning the desired brain signal is strong relative to unwanted background noise. This makes them less susceptible to environmental electrical noise (e.g., from power lines) and motion artifacts compared to other non-invasive electrode types.[1]

Advantages & Disadvantages: The strengths of wet electrodes are rooted in their performance. They provide highly stable signals suitable for recordings lasting several hours and are a trusted, well-understood technology backed by decades of research.[7] Their design can also be adapted for specialized research, such as ring-shaped electrodes that can be integrated into head caps for simultaneous EEG and functional near-infrared spectroscopy (fNIRS) or transcranial magnetic stimulation (TMS) studies.[1] However, these advantages come at a significant cost to usability. The setup process is time-consuming, messy, and requires a skilled technician to apply the gel and ensure low impedances.[1] For the participant, the procedure can be uncomfortable due to the skin abrasion and the unpleasant feeling of gel in the hair, which requires thorough washing afterward. Furthermore, during very long recordings (e.g., over 5 hours), the conductive gel can begin to dry out, causing impedance to rise and signal quality to degrade.[1]

1.1.2 Dry Electrodes: The Pursuit of Usability

Dry electrodes emerged as a direct response to the practical drawbacks of wet electrodes, prioritizing ease of use, speed of setup, and participant comfort.[1]

Description and Materials: A dry electrode is defined by its ability to transduce a signal through direct mechanical contact with the skin, completely eliminating the need for conductive gels, pastes, or skin preparation.[1] This has led to a wide diversity in their design and material composition. Common forms include single, mushroom-shaped pins coated in gold; arrays of multiple spikes or pins designed to part the hair and make contact with the scalp; comb-like or bristle-type structures; and sensors made from conductive silicone rubber or foam.[1]

Performance and Challenges: The convenience of dry electrodes comes with a fundamental electrochemical challenge: the absence of a liquid electrolyte results in a significantly higher skin-electrode contact impedance.[1] This high impedance is the root cause of the primary performance issues associated with dry electrodes. It can lead to a lower SNR, increased signal instability, and a much greater susceptibility to motion artifacts and electrical noise compared to wet electrodes.[1] The quality of the contact is also highly sensitive to factors like hair density, hair type, and scalp condition, making consistent performance more difficult to achieve.[10]

Advantages & Disadvantages: The main advantages of dry electrodes are entirely practical. They allow for extremely rapid setup and require virtually no cleanup, as there is no gel to apply or wash out.[1] This makes them ideal for applications where time is critical, for use in out-of-lab environments, or for consumer-facing products where a trained technician is not available. However, their disadvantages are primarily in signal quality. The high impedance and unstable contact can lead to noisier data, and the rigid nature of many pin-based designs can cause significant discomfort for the wearer, especially during long-term use.[1] Once applied, there are also very limited options for a user to improve the quality of a poor contact.[1]

1.1.3 Semi-Dry and Water-Based Electrodes: A Hybrid Approach

Seeking to bridge the gap between the high fidelity of wet electrodes and the high usability of dry electrodes, a third category of semi-dry or water-based electrodes has been developed. These systems represent a strategic compromise, using a minimal amount of liquid to improve the electrical interface without the mess and complexity of traditional gels.

Description and Materials: This category encompasses several innovative designs. One common type is the sponge-based electrode system (such as the EGI R-Net), which consists of small sponges held in a net that are soaked in a simple saline solution or even tap water before application.[6] Another approach involves solid-gel electrodes, which are made of a hygroscopic material that is hydrated by soaking it in a saline solution for a few minutes before use.[8] More advanced systems may feature electrodes that slowly wick or seep a tiny, contained amount of electrolyte liquid onto the scalp over time.[1]

Performance: By introducing a conductive liquid, these hybrid electrodes effectively overcome the primary challenge of high impedance that plagues purely dry systems. This results in a more stable electrical contact, lower noise levels, and improved signal quality that approaches that of wet electrodes while retaining much of the convenience of dry systems.[1] For example, the hydrated solid-gel electrodes have been shown to maintain stable characteristics for up to eight hours, making them suitable for long recording sessions.[8]

Advantages & Disadvantages: The main benefit of semi-dry electrodes is this balanced profile. They offer significantly faster setup and cleanup than traditional wet electrodes and are generally more comfortable and produce more stable signals than dry electrodes.[1] This makes them a preferred option for many modern research and at-home testing scenarios. Their primary disadvantage is that the minimal liquid they use can evaporate more quickly than thick conductive gel, potentially requiring re-moistening during very long experiments. They also remain more susceptible to artifacts than the gold-standard wet electrodes.[1]

1.1.4 Novel and Soft Electrodes: The Future of Wearable Neurotechnology

At the forefront of electrode innovation is the development of soft, flexible, and biocompatible electrodes designed specifically for long-term, unobtrusive, and wearable applications.

Description and Materials: This emerging class of electrodes moves away from rigid metals and pins and instead utilizes advanced materials science. These include conductive polymers, nanomaterials like graphene (often in its reduced form, rGO) and carbon nanotubes (CNT), and flexible substrates infused with gold nanoparticles.[10] These materials can be printed or patterned onto flexible, skin-like patches or even integrated directly into textiles, creating "smart" clothing or headbands.[13]

Performance and Applications: The defining characteristic of soft electrodes is their ability to conform intimately to the contours of the skin. This flexibility makes them exceptionally comfortable for extended periods of use and allows them to move with the body, which can reduce both discomfort and motion-related artifacts.[10] Their biocompatible nature also minimizes the risk of skin irritation, a common issue with the adhesives and gels used in wet electrode systems.[10] These properties make them the ideal candidates for future applications in continuous, real-world health monitoring and next-generation wearable BCIs.

Advantages & Disadvantages: The unparalleled comfort and biocompatibility of soft electrodes are their key advantages.[10] However, this advanced technology currently comes with significant drawbacks. The sophisticated materials and high-end manufacturing techniques (e.g., nanomaterial deposition, laser patterning) make them considerably more expensive than traditional electrodes.[10] Furthermore, as a newer technology, their performance characteristics, such as long-term signal stability and impedance properties, can vary widely depending on the specific materials and design, and are still an active area of research.[10]

Section 1.2: Active vs. Passive Electrode Architectures

Beyond the method of application, a second, equally critical distinction in electrode technology is the electronic architecture: whether the electrode is passive or active. This distinction directly addresses how the faint neural signal is handled after it is picked up, and it is a key factor in determining the final quality of the recorded data.

1.2.1 Passive Electrodes

Principle: The passive electrode is the traditional and electronically simplest design. It functions as a simple conductor, typically a cup or disc made of Ag/AgCl or gold, which does nothing more than pick up the raw voltage fluctuations from the scalp and transmit them, un-altered, through a long wire to a separate, distant amplifier box.[6]

Limitations: The primary vulnerability of this architecture lies in the transmission of the raw, unamplified signal. The electrical signals from the brain are incredibly small (on the order of microvolts). Transmitting such a weak signal over a wire makes it highly susceptible to contamination from two main sources: ambient electromagnetic noise from the environment (e.g., power lines, electronic equipment) and electrical artifacts generated by the physical movement of the cable itself. To ensure a clean signal reaches the amplifier, it is imperative to start with the strongest possible source signal, which in this context means achieving a very low skin-electrode impedance. For this reason, passive electrodes almost exclusively rely on the use of conductive gel (i.e., they are wet electrodes) to achieve an impedance below 5 kΩ, and ideally below 2 kΩ, for reliable performance.[9]

1.2.2 Active Electrodes

Principle: The active electrode represents a major technological leap designed to overcome the limitations of the passive architecture. In an active electrode system, a miniature pre-amplifier circuit is integrated directly into the housing of each individual electrode.[6] This circuit intercepts the raw brain signal at the moment it is picked up and amplifies it immediately at the source, before it is sent down the wire to the main recording unit.

Mechanism of Improvement: This pre-amplification at the source is a transformative step. By strengthening the signal immediately, the system dramatically improves the signal-to-noise ratio (SNR). The now-robust, amplified signal is far less susceptible to being corrupted by environmental noise or cable movement artifacts during its journey to the main amplifier.[6] This is a crucial innovation, as it effectively circumvents the need for an ultra-low impedance connection. Active electrode technology can produce high-quality recordings even with electrode impedances as high as 500 kΩ.[6] This property is the single most important enabler for modern high-performance dry electrode systems, which would otherwise be too noisy to be useful for many applications.[7]

Features: Modern active electrode systems often incorporate additional useful features. Many include built-in active shielding to further guard against noise, and real-time impedance checking is a common feature. This is often implemented with small LEDs (e.g., red, yellow, green) integrated into the electrode housing, which provide the technician with immediate visual feedback on the quality of the electrode contact, substantially speeding up the setup process.[6]

Performance Comparison: The benefits of this architecture are clear in performance data. Studies have demonstrated that active electrodes provide superior signal quality compared to passive electrodes at all but the very lowest impedance levels. Specifically, passive electrodes only tend to yield higher quality data when impedance is exceptionally low (less than 2 kΩ).[9] When active electronics are paired with dry electrodes, the resulting system can achieve a signal quality that is comparable to that of traditional wet passive electrodes, combining the convenience of a dry setup with the fidelity of an active system.[7]

Disadvantages: The primary drawbacks of active electrodes are their increased complexity and cost. The inclusion of miniature electronic components makes them more difficult and expensive to manufacture than simple passive discs. They may also require additional wiring to provide power and a ground reference to the pre-amplifier circuitry in each electrode.[9]

The entire evolution of non-invasive electrode technology can be understood as a direct response to a fundamental tension between the pursuit of the highest possible signal fidelity and the practical demands for greater usability. This dynamic has propelled a cycle of innovation where solutions to one challenge often introduce a new one, which in turn necessitates further technological refinement. The process begins with the established gold standard: traditional wet Ag/AgCl electrodes provide the highest fidelity but are plagued by usability issues like long, messy preparation and participant discomfort.[1] This created a strong market and research demand for a more user-friendly alternative, leading directly to the development of dry electrodes that eliminate the need for gel and skin preparation.[1]

However, this solution to the usability problem introduced a new, fundamental problem in fidelity. By removing the conductive gel, the skin-electrode impedance increases by orders of magnitude.[7] This high impedance makes the raw neural signal extremely weak relative to environmental noise and highly susceptible to motion artifacts, thus severely degrading signal quality.[9] To solve this new fidelity problem, active electrode technology was introduced. By placing a pre-amplifier directly at the recording site, the signal is strengthened before it can be corrupted by noise, effectively compensating for the high impedance and making dry electrodes a viable alternative.[6] The most recent developments, such as semi-dry, water-based, and soft flexible electrodes, represent the next evolutionary step in this cycle, attempting to synthesize the best of all prior approaches—achieving the low impedance and stability of wet contacts with the comfort and ease of use of dry systems.[1] This ongoing evolution is pushing EEG technology out of the exclusive domain of the clinic and research lab and into the realm of consumer and real-world healthcare applications, a trend enabled by systems that are wearable, suitable for long-term use, and robust enough for out-of-lab monitoring.[1]

Table 1: Comparative Analysis of Non-Invasive Electrode Technologies

Electrode Type	Common Materials	Application Method	Typical Impedance	Signal Quality (SNR, Artifacts)	Comfort	Setup Time	Relative Cost	Key Applications
Wet	Ag/AgCl, Tin, Gold [8]	Requires skin abrasio	Very Low (<10	**Gold Standard:**	Moderate; can be	Long (can be >30	Low to Moderate [10]	Clinical diagnostics,

		n and application of conductive gel/paste [1]	kΩ) [12]	High SNR, low susceptibility to motion/electrical artifacts [1]	uncomfortable due to abrasion and sticky gel [1]	min) [1]		high-precision research (e.g., ERPs) [1]
Dry	Gold-plated pins, conductive rubber/foam, multi-spikes [1]	Direct mechanical contact with scalp; no gel or prep needed [1]	High to Very High (200 kΩ - >1 MΩ) [11]	Lower SNR, more susceptible to motion/electrical artifacts [1]	Varies; can be uncomfortable (pins) or comfortable (foam) [8]	Very Fast (<5 min) [1]	Moderate	Consumer devices, rapid screening, BCI, at-home use [1]
Semi-Dry / Water-Based	Ag/AgCl with sponges, solid hydrogel, wicking polymers [6]	Requires hydration with saline/tap water; no abrasive prep [1]	Low to Moderate (<50 kΩ) [11]	Good; better than dry, approaches wet. More stable than dry [1]	High; more comfortable than both wet and dry pin-based types [1]	Fast (5-10 min) [1]	Moderate to High	Long-term monitoring, research where comfort is key, at-home use [1]
Soft / Flexible	Conductive polymers, graphene, CNTs, printed Ag/Ag	Conforms to skin, often with a minimal adhesive or	Variable; depends on material	Good to Excellent; flexible nature can reduce motion	Very High; designed for maximum comfort in long-te	Fast	High to Very High [10]	Wearable technology, continuous long-term monito

	CI [10]	integrated into textiles [10]		artifacts [10]	rm wear [10]			ring, BCI [10]

Part II: Non-Invasive Electrode Placement: The International Standard Systems

For EEG data to be scientifically and clinically meaningful, it must be reproducible. A critical component of this reproducibility is ensuring that electrodes are placed in the same locations on the scalp every time, across different subjects, laboratories, and recording sessions. To achieve this, a series of international standards have been developed. These systems are based on proportional measurements of the head, ensuring that the placement scheme adapts to individual variations in head size and shape. This section details the evolution of these standards, from the original clinical system to the high-density frameworks required by modern neuroscience research.

Section 2.1: The 10-20 System: The Foundational Standard

The International 10-20 System is the original and most fundamental standard for EEG electrode placement. Its development was a landmark achievement that brought much-needed consistency to the field.

Historical Context and Purpose: The need for a standardized placement method was formally recognized at the first International EEG congress in 1947. Following this, neurophysiologist Herbert H. Jasper undertook studies that resulted in the definition of the 10-20 system in 1958.[5] The system's primary purpose was to create a method that was independent of absolute measurements, instead relying on the proportional relationships between key cranial landmarks. This ensures that the resulting electrode montage is comparable across individuals, making it the de-facto standard for both clinical EEG and foundational research for over half a century.[5]

Measurement Principle: The name "10-20" derives directly from the measurement principle. The distances between adjacent electrodes along the primary contours of the head are either 10% or 20% of the total length of that contour.[20] To apply the system, a technician first identifies four anatomical landmarks: the

nasion (the indentation at the top of the nose, between the eyes), the **inion** (the most prominent bony point at the back of the skull), and the left and right **preauricular points** (the small depressions just in front of the ear tragus).[20] Measurements are then taken along the sagittal plane (from nasion to inion) and the coronal plane (from the left to the right preauricular point) to determine the location of the vertex (Cz) and other key points.

Nomenclature: The 10-20 system specifies the placement and names for 21 electrodes. The nomenclature is systematic:

- **Lobular Regions:** Letters are used to identify the approximate underlying lobe of the brain: **Fp** for frontopolar, **F** for frontal, **C** for central, **T** for temporal, **P** for parietal, and **O** for occipital.[5] It is important to note that the central ('C') electrodes do not correspond to a distinct anatomical lobe but rather serve as a crucial reference line over the sensorimotor cortex.[20]
- **Hemispheric Designation:** Numbers are used to denote the hemisphere. Odd numbers (1, 3, 5, 7) are always on the left side of the head, while even numbers (2, 4, 6, 8) are always on the right.[20]
- **Midline Designation:** Electrodes placed along the central midline (the sagittal plane from nasion to inion) are designated with the letter 'z' for "zero" to avoid confusion with the letter 'O'.[5] This gives rise to the midline electrodes Fz, Cz, and Pz.

Section 2.2: The 10-10 System (Extended 10-20 System): The Move to Higher Density

While the 21 channels of the 10-20 system remain sufficient for many routine clinical applications, the advancement of neuroscience research created a demand for higher spatial resolution to better localize brain activity. This led to the development and adoption of an official extension.

Motivation for Extension: The rise of cognitive neuroscience, particularly the study of Event-Related Potentials (ERPs) and the development of source localization algorithms, required a denser array of electrodes than the 10-20 system provided.[5] Researchers needed to sample the electric field on the scalp with greater detail to pinpoint the origins of neural activity with more accuracy.

Development: In 1985, a logical extension was proposed by Chatrian and colleagues, which involved adding intermediate electrode sites by placing them at every 10% interval along the standard measurement contours, rather than just 10% and 20%.[5] This "10% system," now more commonly known as the

10-10 system, increases the number of standard electrode positions to 74 (within a grid of 81 possible locations).[5] This extended system has since been formally endorsed as the standard by leading professional bodies, including the American Clinical Neurophysiology Society (ACNS) and the International Federation of Clinical Neurophysiology (IFCN), and is often referred to as the "extended 10-20 system".[5]

Modified Combinatorial Nomenclature (MCN): A crucial innovation of the 10-10 system was the introduction of a more systematic and consistent naming convention, the MCN. This addressed certain logical inconsistencies in the original 10-20 system.

- **New Intermediate Rows:** To name the new electrode sites, letter combinations are used to denote the intermediate coronal lines. For example, the row between the Frontal (F) and Central (C) lines is named **FC**. Similarly, new rows include **AF** (between Fp and F), **CP** (between C and P), and **PO** (between P and O), among others.[20]
- **Renaming for Consistency:** To create a more logical grid, several key electrodes from the original 10-20 system were renamed. This is a critical point of knowledge for anyone working with modern EEG systems. The most important changes are:
    - **T3** was renamed to **T7**
    - **T4** was renamed to **T8**
    - **T5** was renamed to **P7**
    - **T6** was renamed to **P8** [5]

    This change resolved an inconsistency where the old 'T' electrodes crossed multiple coronal lines. In the new system, the letter combination more reliably indicates the electrode's position within a consistent coordinate-like framework.22

Section 2.3: The 10-5 System: The High-Density Research Frontier

The cycle of technological advancement continued, with manufacturers developing EEG systems capable of recording from 128, 256, or even more channels simultaneously. This necessitated a framework to standardize the placement of these very high-density arrays.

Motivation: Such high-density recordings are essential for advanced neuroimaging techniques, such as high-resolution source localization, that aim to reconstruct the location of brain activity with a precision that begins to approach that of other neuroimaging modalities like fMRI.[2] The 10-10 system, while a significant improvement, did not provide a standard nomenclature for these much denser montages.

Principle: The **10-5 system** was proposed as a logical continuation of the existing standards. As its name suggests, it is based on using proportional distances of 5% of the total length along the cranial contours.[5] This extension provides a systematic way to name and place over 300 electrodes, offering a standardized framework for the highest-density EEG caps currently in use.[2]

Nomenclature: The naming convention is expanded logically. For instance, an additional coronal contour located between the C-line and the CP-line would be labeled "CCP".[5] This allows for a granular and systematic description of electrode positions across the entire scalp.

Status: It is crucial to understand the official standing of the 10-5 system. While it is widely implemented in research software (e.g., the FieldTrip toolbox for MATLAB) and used by researchers employing high-density systems, it remains a *proposed* extension.[19] As of current guidelines, it has not been formally adopted as an official standard by the major governing bodies like the ACNS or IFCN.[22]

The progression from the 10-20 system to the proposed 10-5 system is not merely an addition of more points; it reflects the tight co-evolution of EEG hardware capabilities and the expanding demands of neuroscience research. The original 10-20 system was perfectly suited for the lower-channel-count machines of its era and the clinical goal of identifying large-scale brain abnormalities.[5] The subsequent rise of cognitive neuroscience created a scientific driver for improved

spatial resolution—the ability to better distinguish between activity from different brain regions.[5] This research demand was met by technological advancements in amplifiers and computing that made higher-channel-count systems (32, 64, etc.)

feasible. The 10-10 system emerged as the necessary standard to bridge this gap, providing a common language for these new capabilities.[5] This cycle is now repeating with 128- and 256-channel systems, for which the 10-5 system provides a necessary, albeit still unofficial, framework.[2] Furthermore, the evolution of the nomenclature itself, such as the renaming of T3 to T7, signifies a deeper shift towards creating a true

coordinate system for the scalp. By ensuring that a letter consistently refers to a coronal line and a number to a sagittal line, the MCN of the 10-10 system transforms the labels from simple names into a logical grid reference.[22] This systematization is indispensable for modern computational analysis, automated plotting routines, and the comparison of data across different high-density recording systems.[19]

Table 2: The International EEG Placement Systems

System Name	Year of Introduction/ Proposal	Typical Electrode Count	Core Principle (% Distance)	Key Nomenclature Features	Status
10-20 System	1958 [5]	21	10% and 20% distances between landmarks [20]	Letters for lobes (F, T, C, P, O), numbers for hemisphere (Odd=Left, Even=Right), 'z' for midline [20]	International clinical and research standard [5]
10-10 System (Extended 10-20)	1985 [5]	74 (up to 81 positions)	10% distances along all contours [5]	Adds intermediate rows (FC, CP, etc.); renames T3/T4/T5/T6 to T7/T8/P7/P8 for consistency [20]	Endorsed international standard for high-density EEG [19]
10-5 System	~2001 [5]	Up to 320+	5% distances along all contours [2]	Further expands nomenclature to	Proposed system for very high-density

				accommodate very high densities (e.g., CCP, AFF) [5]	research; not yet an official standard [22]

Part III: A Spectrum of Invasiveness: From Scalp to Cortex and Beyond

The location of the electrode relative to the brain is the single most important factor determining the quality and type of information that can be recorded. There exists a wide spectrum of recording modalities, organized by their degree of surgical invasiveness. This spectrum is defined by a fundamental and inescapable trade-off: as electrodes move closer to the neural source, signal fidelity increases dramatically, but so do the associated surgical risks, costs, and ethical considerations. This part provides a hierarchical exploration of these methods, from the completely safe scalp EEG to techniques that record from within the brain itself.

Section 3.1: Non-Invasive Modalities: Scalp Electroencephalography (EEG)

This is the most common, accessible, and safest form of electroencephalography, serving as the baseline for all other techniques.

Principle: In non-invasive scalp EEG, electrodes are placed on the surface of the scalp, entirely external to the skull.[23] The procedure requires no surgery and carries minimal risk to the subject.[23]

Signal Characteristics: Scalp EEG records the large-scale, summed electrical activity of millions of synchronously firing neurons, primarily from the superficial layers of the cerebral cortex.[4] Its greatest limitation is the signal degradation that occurs as the electrical fields pass through the layers of tissue between the brain and the electrode. The skull, in particular, acts as a volume conductor and a low-pass filter, which has two major consequences: it spatially blurs the signal, resulting in poor spatial resolution (on the order of centimeters), and it heavily attenuates high-frequency components.[4] Consequently, scalp EEG has the lowest signal-to-noise ratio (SNR) of all EEG modalities and is highly susceptible to contamination from biological artifacts like muscle contractions (electromyography, EMG) and eye bluffs (electrooculography, EOG), as well as external electrical noise.[23]

Advantages: The overwhelming advantages of scalp EEG are its safety and accessibility. It is completely non-invasive, avoiding all surgical risks and potential for brain tissue damage.[23] The equipment is relatively low-cost and often portable, and the procedure is easy to apply and remove, which has enabled its widespread use in clinical diagnostics, academic research, and the burgeoning consumer neurotechnology market.[23]

Limitations: The limitations are all related to signal quality. The low SNR and poor spatial resolution make it difficult to precisely localize brain activity.[4] It is largely limited to analyzing lower-frequency brain waves (typically below 90 Hz) and cannot record any activity from deep brain structures like the hippocampus or amygdala.[4] For brain-computer interface (BCI) applications, these limitations result in the lowest information transfer rates, typically around 5-25 bits per minute.[23]

Section 3.2: Semi-Invasive and Minimally Invasive Modalities

This category represents a critical middle ground, comprising techniques that place electrodes beneath the scalp but outside or on the surface of the brain. These methods aim to achieve a significant improvement in signal quality by bypassing at least one layer of tissue (scalp or skull) without the full risk of penetrating the brain itself.

3.2.1 Electrocorticography (ECoG) / Intracranial EEG (iEEG)

Electrocorticography (ECoG) is a major invasive procedure that involves placing electrodes directly onto the exposed surface of the brain. It is technically a form of intracranial EEG (iEEG), as the electrodes are inside the skull.[32]

Principle and Procedure: The defining feature of ECoG is that it requires a

craniotomy, a major surgical procedure where a section of the skull is temporarily removed to expose the brain.[32] Flexible arrays of electrodes, configured as strips or grids, are then placed on the brain's surface.[32] There are two main variants of this placement:

- **Subdural ECoG (SDE):** This is the most common and classic form of ECoG. The electrode array is placed *underneath* the dura mater, the tough outer protective membrane of the brain. This places the electrodes in direct contact with the pia-arachnoid layers that cover the cortex, as close as possible to the neural source without penetrating it.[23] SDE is considered the gold standard for invasive monitoring to identify the origin of epileptic seizures prior to surgery.[37]
- **Epidural ECoG:** In this less common variant, the electrode array is placed *on top of* the dura mater, between the dura and the skull.[32] Conceptually, this is less invasive because the protective dural membrane is not breached.[35]

Signal Characteristics: By placing the electrodes directly on or near the cortex, ECoG completely bypasses the signal-distorting effects of the skull. This results in a signal that is vastly superior to scalp EEG. The SNR is much higher, the spatial resolution is improved to the millimeter scale, and, critically, it provides clear access to high-frequency brain activity, including the high-gamma band (>70 Hz).[4] This high-frequency activity is strongly correlated with local neural processing and is essential for precisely mapping cognitive and motor functions. The temporal resolution of ECoG is also excellent, at approximately 5 ms.[32]

Comparison of Subdural vs. Epidural: A systematic review comparing the two placements found that while epidural signals are somewhat attenuated in amplitude compared to subdural signals, the ability to decode information from the signals is not significantly affected. Crucially, the review found that the incidence and nature of serious complications were comparable between the two methods, suggesting that both are viable options for long-term implants, with the choice depending on other clinical factors.[35]

Advantages and Limitations: The primary advantage of ECoG is its excellent signal quality relative to non-invasive methods. It also allows clinicians to perform functional mapping of the cortex through direct cortical electrical stimulation (DCES), which is used to identify and preserve critical areas like language and motor centers during surgery.[32] However, it is still a major surgical undertaking with significant risks, including infection and hemorrhage.[23] Its field of view is limited to the area of the cortex exposed by the craniotomy, and it cannot record from deep brain structures or activity occurring within the folds of the brain (sulci).[27] For BCI applications, it offers a moderate information transfer rate of around 40-60 bits per minute.[23]

3.2.2 Subgaleal (SG) and Subdermal Electrodes

This minimally invasive approach offers a compelling compromise between scalp EEG and ECoG.

Principle: In this technique, electrodes are surgically implanted into the space *between the scalp and the skull* (the subgaleal space) or just beneath the skin layer (subdermal).[38] This procedure is significantly less invasive than ECoG as it does not require a craniotomy.

Signal Characteristics and Potential: The key question for this modality is how much signal is lost by not bypassing the skull. A pivotal study that performed simultaneous recordings from subgaleal and subdural ECoG electrodes in the same patients provided a direct answer. The research demonstrated that SG electrodes were indeed capable of recording high-frequency activity in the high-gamma range (70–110 Hz).[38] The analysis of the transfer function suggested that the skull acts as a linear attenuator—it reduces the signal's amplitude but does not selectively filter or distort its frequency content in this range.[38] This is a significant finding, as it implies that meaningful, high-fidelity cortical signals can be obtained using a much safer, less invasive procedure. This modality holds considerable promise for applications like long-term monitoring or BCI systems that require better-than-scalp signal quality without the substantial risks of intracranial surgery.[38]

Section 3.3: Invasive Modalities: Penetrating the Brain

These techniques represent the highest level of invasiveness, placing electrodes directly into the brain's parenchyma to achieve the highest possible signal fidelity.

3.3.1 Stereoelectroencephalography (SEEG or sEEG)

SEEG has emerged as the modern standard for invasive deep brain recording, offering a less traumatic alternative to traditional grid-based ECoG for many clinical scenarios.

Principle and Procedure: Pioneered in France by Jean Talairach and Jean Bancaud, SEEG is a surgical procedure that uses stereotactic guidance—a 3D coordinate system based on pre-operative MRI and CT scans—to precisely implant thin, flexible, multi-contact depth electrodes into specific targets deep within the brain.[27] Instead of a large craniotomy, the surgeon makes a series of very small burr holes in the skull (typically 1.2-2 mm in diameter), through which the electrodes are passed.[27]

Key Application: SEEG is now the preferred method for pre-surgical evaluation in many centers for patients with drug-resistant focal epilepsy, particularly when the seizure onset zone is suspected to be in deep or surgically inaccessible structures, when the exact side of the brain is unknown, or when the seizure network is thought to be spread across multiple lobes.[39]

Signal Characteristics and Coverage: The paramount advantage of SEEG is its ability to provide high-fidelity, three-dimensional sampling of brain activity. It can record directly from deep structures that are completely inaccessible to ECoG, such as the hippocampus, the insula, the amygdala, and the cortex buried within the sulci.[27] This allows for the mapping of entire epileptic networks in 3D. Because the procedure is less traumatic, it also more readily allows for bilateral (both hemispheres) explorations.[41] The signal quality is excellent, with a high SNR, high spatial resolution, and full access to the high-gamma frequency band.[27]

Advantages and Limitations: Compared to SDE, SEEG is less invasive, results in less post-operative pain, and has a lower rate of major complications.[34] Its ability to map deep 3D networks is unparalleled. Its primary limitation is that it provides a much sparser sampling of the broad cortical surface compared to a high-density ECoG grid. This can make it more challenging to map widespread functions that lie on the surface of the gyri.[27]

3.3.2 Intracortical Microelectrode Arrays (MEAs)

This is the most invasive recording modality and represents the current frontier of human brain-computer interfaces, offering a window into the most fundamental level of neural processing.

Principle: This technique involves the surgical implantation of arrays of microelectrodes (a well-known example being the "Utah Array") that have tiny conductive tips designed to penetrate the first few millimeters of the cerebral cortex.[4]

Signal Characteristics: The defining feature of MEAs is their ability to record the activity of **individual neurons**. While all other EEG methods record the summed, population-level activity of thousands or millions of cells (Local Field Potentials, or LFPs), the fine tips of microelectrodes can be placed close enough to individual neurons to detect their action potentials, or "spikes".[4] This provides the highest possible spatial and temporal resolution and the highest fidelity signal of any human neurophysiological recording technique.

Advantages and Limitations: The ability to record single-unit activity is the primary advantage, as it provides access to the brain's fundamental computational code. This allows for the highest information transfer rates for BCI applications, estimated at around 100-200 bits per minute, which is necessary for the nuanced control of advanced robotic prosthetics.[23] However, this comes at the cost of the highest risk. The procedure requires a craniotomy and penetration of brain tissue, carrying risks of tissue damage and hemorrhage. Furthermore, the long-term stability of these implants is a major challenge. The brain's natural foreign body response can lead to the formation of scar tissue (gliosis) around the electrode tips, which can degrade the signal quality over months or years, requiring recalibration or replacement.[23]

The relationship between invasiveness and the quality of information obtained is not merely a linear continuum; it is better understood as a series of distinct, step-like gains in the *type* of information that becomes accessible. The first major step is from non-invasive scalp EEG to semi-invasive ECoG. This is a qualitative leap because it overcomes the single greatest physical barrier: the skull. The skull acts as both a spatial low-pass filter that smears the signal and an attenuator that weakens it.[4] Placing electrodes directly on the cortex bypasses this barrier, granting access to high-frequency signals like the high-gamma band and improving spatial resolution from centimeters to millimeters.[27] This is a fundamental change in the available data.

The second step is from the 2D surface mapping of ECoG to the 3D volumetric sampling of SEEG. While ECoG provides a high-density map of the cortical surface, it cannot access the vast areas of cortex buried within sulci or the critical deep structures like the hippocampus and insula.[37] SEEG's ability to place electrodes deep within the brain provides a true three-dimensional understanding of neural networks, which is impossible with surface-only methods and is essential for mapping complex seizure networks.[27]

The final step is from recording population activity with macroelectrodes (ECoG, SEEG) to recording the firing of individual neurons with microelectrode arrays (MEAs). ECoG and SEEG record Local Field Potentials (LFPs), which represent the summed input to a local population of cells.[4] MEAs can resolve the action potentials, or "spikes," which are the output signals of single neurons.[4] This provides access to the most fundamental unit of neural computation. This hierarchical structure implies that the choice of modality should be driven by the specific scientific or clinical question at hand.

This understanding has fueled a significant trend towards developing and utilizing "minimally invasive" options that occupy the strategic middle ground. The field is moving beyond a simple binary choice of invasive versus non-invasive and towards a richer spectrum of technologies. Techniques like subgaleal electrodes [38], epidural ECoG [35], and SEEG itself (which is considered minimally invasive

relative to a large craniotomy) [34] are all part of this trend. The goal is to precisely match the level of invasiveness, with its associated risk and cost, to the specific information required for a given clinical or research application, enabling a more nuanced and patient-specific approach to neurophysiological monitoring.

Table 3: Hierarchy of Electrophysiological Recording Modalities by Invasiveness

Modality	Surgical Procedure	Proximity to Neurons	Primary Signal Type	Spatial Resolution	Temporal Resolution	Access to Deep Structures	Key Advantages	Key Limitations / Risks	BCI Info Rate (bits/min)
Scalp EEG	None (Non-Invasive)	External to skull	Scalp Potentials (summed activity of very large populations)	Low (centimeters) [26]	Excellent (milliseconds) [26]	No [23]	Safe, low-cost, portable, easy to use [23]	Low SNR, high artifact susceptibility, signal blurred by skull [4]	~5–25 [23]

Subgaleal (SG) EEG	Minor surgery (incision)	Between scalp and skull	Cortical Potentials (including High-Gamma)	Moderate (better than scalp)	Excellent (milliseconds)	No	Less invasive than ECoG, better signal than scalp EEG, can record HG [38]	Still requires minor surgery; signal attenuated by skull [38]	N/A
Epidural ECoG	Craniotomy	On top of dura mater	Local Field Potentials (LFP)	High (millimeters)	Excellent (~5 ms) [32]	No	Bypasses skull, good signal quality, dura remains intact [35]	Major surgery, risk of infection/hemorrhage, limited field of view [32]	~40–60 [23]
Subdural ECoG (SDE)	Craniotomy	On cortical surface (under dura)	Local Field Potentials (LFP)	High (millimeters) [32]	Excellent (~5 ms) [32]	No (only surface) [27]	Highest surface signal quality, allows for cortical stimulation mapping [32]	Major surgery, higher complication risk than SEEG, cannot access sulci [34]	~40–60 [23]
SEEG	Burr	Deep	Local	High	Excell	Yes [27]	3D	Spars	~40–

	holes	in brain parenchyma	Field Potentials (LFP)	(millimeters) [27]	ent (milliseconds)		mapping of deep structures, less invasive than craniotomy, lower complication rate [34]	er cortical sampling than grids, risk of hemorrhage along tracks [27]	60 (estimated)
Microelectrode Arrays (MEAs)	Craniotomy & cortical penetration	Intracortical (adjacent to neurons)	Action Potentials ("Spikes") & LFP	Very High (single neuron) [4]	Excellent (sub-millisecond)	Limited to implant depth	Records single neuron activity, highest signal fidelity [4]	Highest surgical risk, tissue damage, long-term implant instability [23]	~100–200 [23]

Part IV: Comparative Analysis and Application-Specific Considerations

The selection of an appropriate EEG technology is not made in a vacuum; it is dictated by the specific goals of the application. A technology that is ideal for a low-cost consumer product would be dangerously inadequate for pre-surgical planning. This final part synthesizes the preceding technical information to explore how these different modalities are applied in real-world contexts. It provides a detailed, evidence-based comparison of the two leading invasive techniques and examines the practical economic factors that influence technology adoption.

Section 4.1: A Synthesis of Applications

The versatility of EEG has led to its application across a wide range of domains, from critical medical diagnostics to cutting-edge neuroscience research and consumer technology.

4.1.1 Clinical Diagnostics

In the medical field, EEG is an indispensable tool for the diagnosis and management of numerous neurological conditions.

- **Epilepsy and Seizure Disorders:** This remains the most important and widespread clinical application of EEG. A standard, non-invasive scalp EEG is the primary diagnostic procedure used to detect the abnormal electrical discharges characteristic of epilepsy, help classify seizure types, and identify epilepsy syndromes.[13] In cases of drug-resistant epilepsy where surgery is being considered, but the exact origin of the seizures cannot be determined non-invasively, invasive monitoring with ECoG (SDE) or SEEG is employed to precisely localize the epileptogenic zone for surgical resection.[32]
- **Sleep Disorders:** EEG is the gold-standard technology for the objective study of sleep. Polysomnography (a comprehensive sleep study) relies on EEG to identify the distinct brain wave patterns associated with the different stages of sleep (e.g., NREM stages 1-3, REM sleep). By analyzing this sleep architecture, clinicians can diagnose a wide range of sleep disorders, including insomnia, narcolepsy, and sleep apnea.[13]
- **Other Neurological Conditions:** The utility of EEG extends to many other conditions. It is used to evaluate patients with altered mental status or coma to assess the degree of encephalopathy (a diffuse disease of the brain).[45] It can help diagnose specific conditions like brain inflammation (encephalitis) or Creutzfeldt-Jakob disease, monitor for ischemic changes after a stroke or hemorrhage, and is a key component in the clinical determination of brain death.[13]

4.1.2 Brain-Computer Interfaces (BCIs)

BCIs are systems that create a direct communication pathway between the brain and an external device, allowing a user to issue commands using only their thoughts.[15] The choice of EEG modality is critical to a BCI's performance.

- **Non-Invasive BCIs:** These systems almost exclusively use scalp EEG due to its safety and ease of use. They are best suited for applications that do not require highly nuanced control. Examples include communication systems for individuals with "locked-in" syndrome, control of simple devices based on motor imagery (e.g., imagining moving a hand), and neurofeedback training for conditions like ADHD and anxiety.[13] The main constraint is the low information transfer rate, which limits the speed and complexity of control.[23] This category also includes the growing market of consumer BCIs for applications like meditation aids and gaming.[31]
- **Invasive BCIs:** These are reserved for performance-critical applications where the highest possible degree of control is required. Using signals from ECoG, SEEG, or, most powerfully, intracortical microelectrode arrays, these BCIs can achieve much higher information transfer rates. This enables sophisticated applications such as the control of multi-degree-of-freedom prosthetic limbs for individuals with paralysis, allowing for the restoration of complex motor functions.[15] The unique ability of SEEG to record from deep brain structures opens up novel BCI possibilities, such as decoding navigational intent from the hippocampus or emotional states from the limbic system.[27]

4.1.3 Neuroscience and Cognitive Research

Beyond the clinic, EEG is a workhorse of modern neuroscience, providing invaluable insights into brain function with unparalleled temporal resolution.

- **Mapping Cognitive Processes:** Cognitive psychologists and neuroscientists use EEG to study the neural underpinnings of mental processes like attention, perception, memory, language, and emotion.[13] The high temporal resolution of EEG (on the order of milliseconds) makes it ideal for understanding the precise timing of these cognitive events.

- **Event-Related Potentials (ERPs):** A powerful research paradigm involves averaging the EEG signal over many trials that are time-locked to the presentation of a specific stimulus or event. This technique extracts the brain's stereotyped response, known as the ERP, from the background noise. Specific ERP components, like the P300 wave (a positive deflection occurring about 300 ms after a novel stimulus), are widely used as biomarkers of cognitive processes like attention and context updating.[26]
- **Neuromarketing and Human Factors:** In the commercial world, EEG is increasingly used as a tool for "neuromarketing." By measuring a consumer's brain activity while they view an advertisement or interact with a product, researchers can gain objective, implicit insights into their engagement and emotional response, which may not be captured by traditional surveys or focus groups.[3]

Section 4.2: Head-to-Head Comparison: SEEG vs. Subdural Grids (ECoG/SDE)

The choice between the two primary invasive monitoring techniques for epilepsy surgery—subdural grids (SDE) and stereoelectroencephalography (SEEG)—is one of the most significant clinical decisions in the field. A recent and compelling body of evidence has emerged that directly compares their effectiveness, fueling a notable shift in clinical practice worldwide.

Context and Procedural Differences: For decades, the choice between SDE and SEEG was often guided by the historical practice and expertise of a given institution rather than by robust comparative data.[34] The procedures are fundamentally different. SDE involves a large craniotomy to place high-density electrode grids on the surface of the cortex, providing excellent spatial sampling of that surface.[34] SEEG, in contrast, is a less invasive procedure that uses small burr holes to place depth electrodes, allowing for the exploration of deep, bilateral, or multi-lobar targets at the cost of sparser cortical surface coverage.[27]

Comparative Effectiveness Evidence: Recognizing the lack of high-level evidence to guide this choice, the Surgical Therapies Commission of the International League Against Epilepsy (ILAE) established a large, international registry of patients who underwent invasive monitoring. Using sophisticated statistical methods (propensity score matching) to create comparable patient cohorts, this study provided the most rigorous comparison of the two techniques to date.[34] The key findings were as follows:

- **Likelihood of Proceeding to Resection:** The analysis revealed that patients who underwent an SDE evaluation were significantly *more likely* to proceed to a subsequent resective surgery compared to those evaluated with SEEG. The odds ratio was approximately 1.4, meaning the odds of having surgery were about 40% higher after an SDE investigation.[34]
- **Seizure Freedom Outcome:** This finding was contrasted sharply by the surgical outcomes. Among the patients who did have surgery, those whose resections were guided by SEEG were significantly *more likely* to achieve long-term seizure freedom. The odds of being seizure-free were 1.66 times higher for the SEEG group.[34] The unadjusted data showed a stark difference: approximately 55% of patients in the SEEG-guided group became seizure-free, compared to only 41% in the SDE-guided group.[34]
- **Complication Rates:** The safety profiles of the two procedures were also markedly different. The SDE procedure was associated with a significantly *higher* rate of major complications, which included post-operative infection, symptomatic intracranial hemorrhage, or new, permanent neurological deficits. The odds of a major complication were 2.24 times higher for SDE compared to SEEG.[34] The raw complication rate was 9.6% for SDE versus just 3.3% for SEEG.[34]

Interpretation of Findings: This evidence paints a clear and compelling picture. While an SDE evaluation may more frequently lead to a decision to operate, the surgeries that follow a SEEG evaluation are both safer and more likely to be successful in rendering the patient seizure-free. This suggests that the superior ability of SEEG to map deep and complex 3D seizure networks leads to more precise and effective surgical targets. The higher rate of resection following SDE may, in some cases, reflect a decision to operate based on less precise information, leading to a lower success rate. This high-level evidence is a primary driver of the ongoing global shift in clinical practice towards favoring SEEG for many patients with difficult-to-localize epilepsy.

Table 4: Evidence Summary: SEEG vs. Subdural Electrodes (SDE) for Epilepsy Surgery

Outcome Metric	SDE Result	SEEG Result	Interpretation	Source
Likelihood of Resection	Higher odds of proceeding to resection (OR ≈ 1.4)	Lower odds of proceeding to resection	SDE evaluations are more likely to result in a surgical procedure.	34

Seizure Freedom Rate (Post-Resection)	Lower odds of seizure freedom (41% unadjusted rate)	Higher odds of seizure freedom (OR ≈ 1.66) (55% unadjusted rate)	SEEG-guided resections are more likely to be successful in stopping seizures.	[34]
Major Complication Rate	Higher odds of complications (OR ≈ 2.24) (9.6% unadjusted rate)	Lower odds of complications (3.3% unadjusted rate)	SEEG is a significantly safer procedure with a lower risk of major adverse events.	[34]

Section 4.3: Economic and Usability Factors

The practical considerations of cost and usability are critical factors that often dictate which EEG technologies are adopted in different settings. The financial investment required for EEG systems spans several orders of magnitude.

Cost Spectrum of EEG Systems:

- **Consumer-Grade Systems:** At the most accessible end of the spectrum are consumer-grade devices, which are typically priced under $1,000. Brands like NeuroSky, Muse, and OpenBCI offer systems with a low number of channels (1 to 16) and are primarily designed for non-critical applications such as meditation, cognitive training, or educational purposes. They prioritize low cost and ease of use, often employing wireless, dry-electrode technology.[14]
- **Research-Grade Systems:** This category represents a significant step up in both capability and cost.
  - **Mid-Range ($1,000 - $25,000):** This tier includes systems from companies like ANT Neuro, G.tec, mBrainTrain, and Brain Products. They typically offer between 8 and 64 channels and often feature advanced capabilities such as wireless data transmission and the option to use dry or saline-based electrodes to reduce setup time. These are the workhorses of many academic research labs.[14]
  - **Premium (> $25,000):** The highest tier of non-invasive systems is designed for cutting-edge neuroimaging research. Brands like BioSemi and ANT Neuro offer systems with very high channel counts, ranging from 128 up to 256 or

more. The immense cost is justified by the extremely high spatial resolution these systems provide, which is necessary for advanced source localization analyses.[14]

- **Clinical and Invasive Systems:** While specific price lists are not publicly available, the cost of systems used for clinical diagnostics and invasive monitoring is implicitly the highest. These costs encompass not only the specialized, medical-grade hardware and software but also the substantial expenses associated with surgical procedures, prolonged hospital stays in specialized monitoring units, and the highly trained personnel required to perform and interpret the studies.[23]

Electrode and Consumable Costs: Beyond the initial capital investment in an amplifier system, the recurring costs of electrodes and consumables are also a practical consideration. Reusable cup electrodes made of gold or Ag/AgCl are sold in packs of 10 or 12, with prices typically ranging from approximately $100 to $250 per pack.[16] Disposable electrodes, including both sticky pads and single-use cups, are also widely available, with prices varying from less than a dollar to several dollars per electrode depending on the type and quantity.[52] The sterile, single-use needle and depth electrodes required for subdermal and intracranial procedures represent a further category of specialized, higher-cost consumables.[51]

The vast diversity of EEG applications, from medical diagnosis to consumer wellness, has created an equally diverse technological landscape. There is no single "best" EEG technology; rather, the field operates on a "right tool for the job" principle. The optimal system is the one that provides the necessary balance of signal fidelity, invasiveness, risk, usability, and cost for a specific task. A low-cost, dry-electrode consumer headset is the correct choice for a meditation app, where safety and ease of use are paramount. A high-density, wet-electrode research system is the correct choice for a non-invasive ERP study requiring high signal quality. An invasive SEEG or SDE procedure is the necessary choice for an epilepsy patient needing surgical evaluation, where the diagnostic yield justifies the risk. Finally, an implanted microelectrode array is currently the only viable option for a high-performance motor BCI that can restore nuanced function to a paralyzed individual. Understanding these application-specific requirements and the capabilities of each technology is the hallmark of expertise in this field.

Conclusion

The field of electroencephalography has evolved dramatically from its origins into a sophisticated and multifaceted domain of science, medicine, and engineering. This review has systematically analyzed the three core pillars of the technology: the electrodes themselves, the standardized systems for their placement, and the spectrum of procedural invasiveness. Several key principles emerge from this comprehensive analysis.

First, the development of EEG technology is fundamentally driven by a persistent trade-off between **signal fidelity and practical usability**. From the high-fidelity but cumbersome wet electrodes to the convenient but noisy dry electrodes, and the hybrid systems that seek to find a middle ground, each innovation can be understood as an attempt to optimize this balance for a particular application. The advent of active electrode technology has been a pivotal development, significantly mitigating the fidelity-usability trade-off by enabling high-quality signals even from high-impedance dry contacts.

Second, the standardization of electrode placement, progressing from the clinical 10-20 system to the high-density 10-10 and proposed 10-5 systems, directly mirrors the co-evolution of hardware capabilities and research demands. This progression has not only enabled higher spatial resolution but has also transformed the nomenclature into a true coordinate system for the scalp, a critical step for modern computational neuroscience.

Third, the relationship between invasiveness and information is not linear but is characterized by a **step-function of information gain**. Moving from the scalp (EEG) to the cortical surface (ECoG) bypasses the skull, unlocking high-frequency signals. Moving from the 2D surface to the brain's 3D volume (SEEG) reveals deep anatomical networks. Moving from population-level recordings to single-neuron activity (MEAs) provides access to the brain's fundamental computational code. This hierarchy underscores that the choice of modality is dictated by the specific type of information required.

Finally, the recent, evidence-based shift in clinical practice from subdural grids to SEEG for epilepsy surgery highlights a maturing field. It demonstrates how large-scale, collaborative data analysis can provide clear guidance on complex clinical decisions, ultimately leading to safer procedures and better patient outcomes. The future of electrophysiological brain interfaces will likely involve a continued diversification of this technological toolkit, with an emphasis on developing minimally invasive and wearable systems that can bring the power of brain monitoring out of the lab and into real-world environments, further expanding the frontiers of neuroscience and clinical care.

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