RP Materials: Proceedings (e-ISSN: 2583-8342)
Vol. 5, Part 1 (2026) pp. 81–85

Cite this article: S. Singh, P. Sheoran, M. Duhan, Insight towards: advanced biomedical material for specialized scalp signal acquisition electrode for cerebral electrophysiological assessment of neural circuitry, *RP Materials: Proceedings* Vol. 5, Part 1 (2026) pp. 81–85.

Review Article

Insight towards: advanced biomedical material for specialized scalp signal acquisition electrode for cerebral electrophysiological assessment of neural circuitry

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[**]Selection and Peer-Review under responsibility of the Scientific Committee of the 4th International Conference on Recent Trends in Materials Science & Devices 2026 (ICRTMD 2026) held at JVMGRR College, Charkhi Dadri, Haryana, India during 6–8 April 2026.

ARTICLE HISTORY
Received: 04 April 2026
Revised: 27 May 2026
Accepted: 27 May 2026
Published online: 12 June 2026

KEYWORDS
Global; EEG electrode; 3-D flexible printer technology; 128-Channel; Synthesis; Advanced biomaterial.

ABSTRACT
Despite global application of EEG both at clinical and research level, main concern towards interfacing between skin-electrode depends of suitable selection of biomaterial for designing a scalp electrode. So, this survey effectively demonstrates a comprehensive insight towards design as material of neuro circuitry scalp electrode. For EEG electrode we need to design a specialized-electrodes as scalp is not flat and head region consists of hair like unequal platform. So, finger-like small size (less interference of noise) electrodes are used, for these we need a 3-D flexible printer technology. The Ag/Ag chloride coating is employed for enhancing efficiency. All the properties of electrodes are enhanced with adorable material employed for synthesis. Recent survey covers advanced biomaterials such as conductive polymers, composites of nanomaterials, flexible substrate enhancing conforming and signal strength. It also highlights advantages, drawbacks of each material with much improved possible future aspects.

1. Introduction

Hans Berger in 1920's introduced word Electroencephalography (EEG), also called them as burger waves. This is main revolution in world of neurology with the help of only two brain electrodes [1]. The EEG signals are recorded from brain cells also known as neuron [2]. The most comprehensive system consists of scalp electrodes, some filters, signal conditioning amplifiers, A to D converter (ADC), measuring, analysing and recording device [3]. The main concern of our survey is on scalp electrodes which is employed for detecting EEG signals; lies in frequency of 0.5 to 120 Hz, including delta, theta, alpha, beta and gamma waves and amplitude lie from 1µv to 100 µv [4].

The main elementary component capturing brain signal directly attached to scalp is known as electrode. The choice of electrode material is very important in measuring quality of cortical signal. The traditional electrode is made up of Ag/AgCl material with electrolyte gel coating on it to reduce interference and to enhance conductivity. Other electrodes are semi-dry EEG scalp electrode [5], porous ceramic based, polyacrylamide/ polyvinyl alcohol super-porous hydrogel infused semi-dry EEG electrode are developed [6].

The electrolyte infused electrode shows low impedance due to presence of free charge. The wet (electrolyte infused) EEG electrode consumes more time as compared to dry electrode. The gel must be cleaned from hair after cortical signal recording every time; this process requires additional time. Sometimes, it captures noise and in long-time EEG tracing, gel becomes dry and leads to decline in quality of signal [7]. Additionally, electrolyte gel may cause some allergic reaction [8].

The dry EEG electrode enables portable type of EEG device that can be easily taken from one place to another place. It also allows self-monitoring of cortical signal after guided training; one can easily perform experiment. Dry EEG electrodes are comprised of carbonaceous materials, polymers, oxides and some metals. The potential applications are in field of cognitive neuroscience for recognition of Alzheimer, migraine, depression, Parkinson's whereas, other applications are in treatment and BCI (Brain Computer Interfacing).

Hinrichs et al., [9] and Radun tz et al., [10] differentiate performance of dry/wet EEG electrode for neuro application based on evidence it is cleared that dry electrodes are preferred over gel-based electrode at level of diagnosis and treatment. The potential challenges for dry EEG electrodes are SNR

(Signal to noise ratio), skin-electrode impedance and quality of EEG signal. The branch of material science working on it to improve relevant features [11]. The main concern of this review article is on material used for preparing electrode with respective pros, cons, cost, real world applications and challenges.

2. Materials, technology and discussions

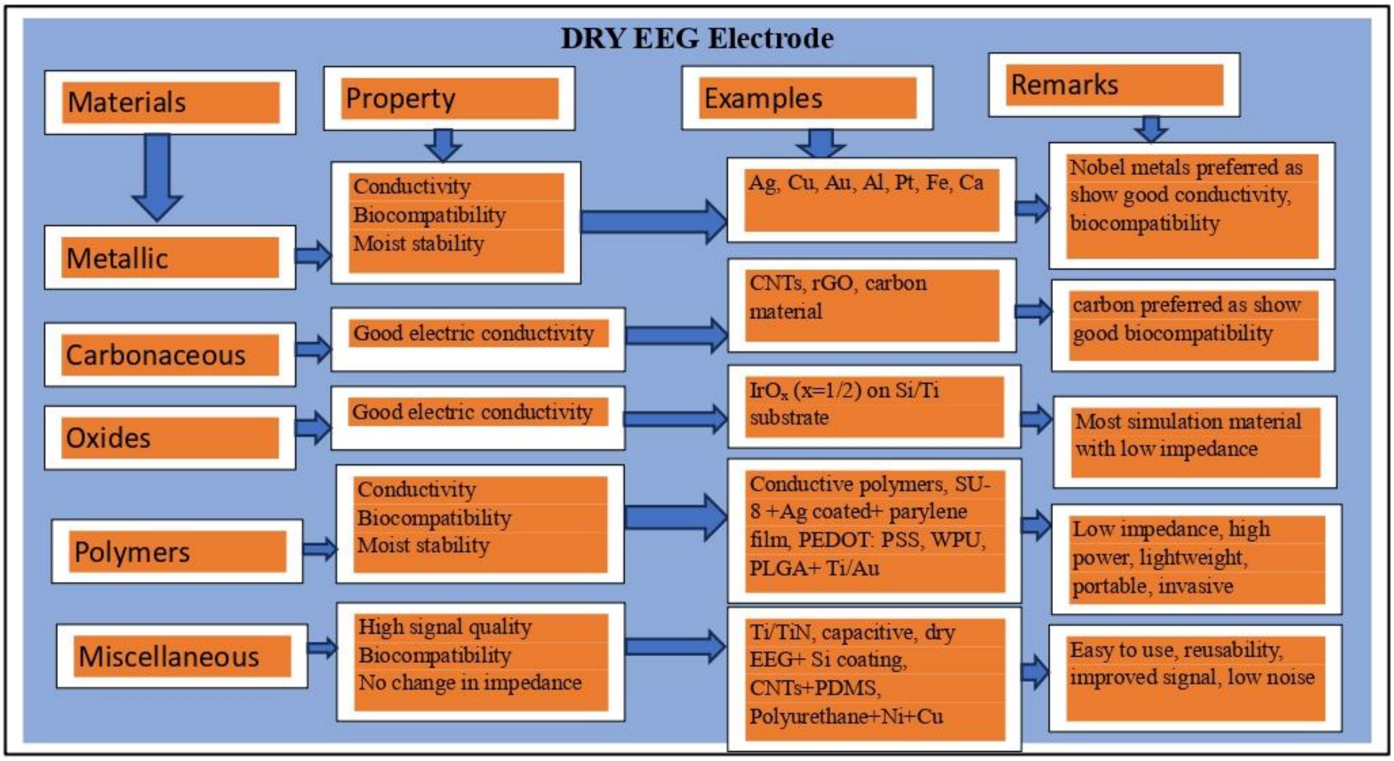

Figure 1: Material for dry EEG electrode.

There are numerous methods employed for fabricating EEG electrode; can be classified into metallic, carbon compound based (carbonaceous), oxides, polymers and miscellaneous as described in flowchart of Figure 1.

From, comparative study of all, described in table 1; we come to reach a point that metals exhibit high conductivity so, recommended for fabrication of surface cortical electrode. Mainly traditional cortical electrode is known as Ag/AgCl (silver/silver chloride) electrode. The other property is biocompatible and easy to use.

Table 1: Different scientific study for preparation of EEG electrode.

Scientist name	Research	Method	Conclusion
Metals			
Mukundan et al., 2019 [12]	Ag/AgCl electrode	Solid state	Costly, utilize more Ag (silver) powder. Use electrochemical method to reduce cost.
Rootare and Powers, 1977 [13]	Ag/AgCl electrode	Electrolysis	Ag- anode, Hcl/Kcl solution are used.
Griss et al., 2001 [14]	Ag/AgCl electrode	Mechanical + electrochemical merged	Mechanical (for coating) AgCl (0.9 M) chloride solution used as electrolyte.
Li et al., 2020 [15]	Printable Ag/AgCl electrode	3-D printing technology	Sweat proof electrodes are prepared.
Zhu et al., 2015 [16]	Ag nanowire configured electrode (AgNWs)	Ag nanowire	AgNWs +poly-dimethylsiloxane. Nanowire have large surface area and conductivity. High electrical amplitude than traditional Ag/AgCl EEG electrode.
Zhu et al., 2019 [17]	AgNWs prepared with printing technology having conductivity= 5.6×10^6 sm^{-1}	Electro-hydro dynamic printing	More intensive EEG signal captured with these electrodes.
Yang et al., 2012 [18]	Au (gold) coating on PDMS substrate	Sputtering	~0.2 μm Au layer coated, more flexible PDMS based electrode. AgCl impedance=10-30 KΩ, Au coated=5-10 KΩ
Someya et al., 2018 [19]	Au very thin film, dry electrode	Thermal deposition	Au= ~300nm, noise↓, impedance↓
Kim et al., 2018 [20]	Pt dry EEG electrode	Electro-deposition	NaCl +Hexachloro platinic acid. Pt foil= electrolyte Pt electrode impedance=10 KΩ EEG signal acquisition up to 96% (hairy occipital

			lobe and forehead region)
Yang et al., 2014 [21]	Ag/Ti EEG electrode	-----------	Ag=400 nm thick Ti=15 nm thick (adhesive) Average correction level= 92% and shows half impedance than traditional Ag/AgCl
Sancrott et al., 2007 [22]	Multilayer EEG electrode prepared with Cu, Pb and Au	Electroplating (Cu), laser deposition (Au Pb), thermal deposition (Au)	Au= so nm SNR = lower Amplitude= lower (as compared to traditional)
Liao et al., 2011 [23]	BeCu non-magnetic alloy used for making EEG electrode, Au probe coated	Non-magnetic Au deposition	Low impedance shown due to BeCu alloy. Correction= 98% (standard wet electrode)
Carbonaceous material			
Silva et al., 2008 [24]	CNTs are designed for EEG examination	PECVD (Plasma-Enhanced Chemical Vapour Deposition)	Brush like 50 nm CNTs biocompatible to human scalp skin. Diminished/ reduced skin-electrode impedance by improving quality of brain signals
Lee et al., 2014 [25]	Flexible dry EEG electrode is prepared by combining CNS with PDMS	2-step dispersion approach	Shows less impedance, good signal quality compared to traditional Ag/Ag Cl with better mechanical performance, biocompatibility and comfort for subject
Li et al., 2020 [26]	rGO (graphene oxide) material used to established EEG electrode	Hummers	Shows good mechanical, good signal quality with signal correction above 75%
Park et al., 2020 [27]	Nylon with rGO (graphene oxide) mixed to form flexible dry EEG electrode	Hummers	Shows high biocompatibility due to presence of rGO in electrode
Mao et al., 2019 [28]	rGO based dry EEG electrode	Laser pattering	More biocompatible, low impedance electrode formed
Sivasankar et al., 2019 [29]	rGO based dry EEG electrode	Electrochemical exfoliating	More biocompatible, low impedance electrode formed
Oxides material			
Correia et al., 2012 [30]	Iro (iron oxide) coated Si substrate electrode	Sputtering	Iro oxoides show low impedance as compared to traditional Ag/AgCl
Kidmose et al., 2019 [31]	Ear dry EEG electrode (Iro+Ti substrate)	Thermal deposition	IrO_2 shows very negligible impedance and quality of signal improved
Polymers			
Lee et al., 2018 [32]	PDMS dry EEG electrode+ CNTs	High energy sonication	Power and performance of this electrode is less as compared to traditional Ag/AgCl
Miki et al., 2015 [33]	SU-8 coated with silver (Ag) and film of parylene for fabrication of needle type EEG electrode	Fabrication with coating	Low impedance, high power invasive type penetrating electrode
Lee et al., 2009 [34]	PI (Polyimide-based EEG electrode	------------	Conductivity improved
Lee et al., 2010 [35]	PI +Ti+ Au combined electrode formed	Full-cured	↑enhanced (more improved conductivity, extreme good biocompatibility
Jiang et al., 2016 [36]	Micro needle EEG electrode with PLGA +Ti+ Au coating	-----------	Biocompatible + conductive, impedance ↓, extra gel and skin preparation not required, invasive
Chen et al., 2016 [37]	PEDOT +dry electrode	Dip coating	Conductive. Biocompatible, suitable for bioelectric activity
Bergeler et al., 2018 [38]	PEDOT +dry electrode	Light-cured	Low impedance, good stable signal, high conductivity, reusable, non-invasive
Miscellaneous			
Lin et al., 2014 [39]	Dry EEG electrode +Si conductive semiconductor	--------------	Subjects comfort, contact impedance↑ and PSD (Power Spectral Density) with Si electrode is less than traditional Ag/AgCl
Fonseca et al., 2009 [40]	Tix_n coated EEG electrode	-----------------	Low noise
Haueisen et al., 2015 [41]	Ti/Ti N dry EEG electrode	DC magnetron sputtering	Peak is high in Ti/TiN based electrode acquired EEG signal, no change in impedance
Park et al., 2012 [42]	Capacitive EEG electrode Polyolefine (PF) foam on PU (Poly-Urethane) + Ni+Cu (Copper)	Separation of charge in two capacitor plate	Low impedance, perfect for hairy scalp, signal improved
Lee et al., 2016 [43]	Capacitive EEG electrode CNTs+PDMS Parylene C insulated layer	Coating	Improved EEG signal, no change in impedance, easy to apply, reusable

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The method of preparation is different for distinct electrode; for making a perfect electrode that is described well in table 1. Some methods for metal cortical electrode are solid state [12], electrolysis [13], mechanical+ electrochemical [14], 3-D printing technology [15], silver nano wires [16], electrohydrodynamic printing [17], sputtering [18], thermal deposition [19] and electroplating laser deposition [22]. Whereas; for carbon containing electrode most precise methods are PECVD (Plasma Enhanced Chemical Vapour Deposition) [24], hummers [26], [27], laser pattering [28], electrochemical exfoliating [29] and sputtering [30]. The polymers are highly recommended for making electrode of scalp as flexible nature with good biocompatibility. So, it is used for recording bioelectric signal other than EEG also such as EMG and ECG. The methods used are high energy sonication [32], full-cured [35], light-cured [38]. Similarly, some other EEG electrode materials such as Si coated electrode, Ti/TiN dry EEG electrode, CNTs+PDMS are prepared by DC magnetron sputtering [41], capacitive separation of charge [42] technique.

3. Conclusions and future perspectives

EEG electrodes are main component of brain signal examination to monitor the bioelectric activity of neural system. It is recommended for heath surveillance and neural-computer interfacing. Dry electrodes are best alternative to traditional wet EEG electrodes that requires more time, skin allergy/ irritation with gel, long-term limitation. The setup of wet electrode system is also complex. The advancement in field of material engineering aids revolution in electrode designing mainly in polymer, CNTs, graphene oxide, metal-based electrode that enhances cortical signal quality, also aids comfort to patient and reusable biocompatible characteristics. Microneedle electrode formation diminished the artefacts.

Irrespective, of advantages these electrodes are associated with challenges in reducing skin-electrode impedance, cost, stability issue, long time durability and biocompatibility. If we consider future perspective the main focus should be on fabrication of multifunctional biocompatible materials suitable for hair containing structure of scalp; in order to maintaining proper management of conductivity.

The upcoming technology of artificial intelligence can be utilized while designing electrode using 3-D printing technology for soft and self-healed electrode materials for enhancement in durability and making long-time monitoring comfortable. The design should be like that electrode must be less invasive and bio-inspired by maintaining safety. The wireless EEG setup is demand of upcoming generation, which is light-weight, portable, cost effective, consumes very less time and power by reducing noise level. In this end, collaboration between various discipline such as material engineering, artificial intelligence, clinicians, scientist, neuro technology and nano technology is essential to improve limitation by proving real wired adoption.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Data availability

No new data were created.

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