

Characterization of dry Graphite MWCNT hybrid ECG electrodes and the role of biocompatible surfactants fabrication additive on the bio-signal responses

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This study involves fabrication of a ‘dry’ electrocardiography (ECG) surface electrode using multi-walled carbon nanotubes (MWCNT) and graphite as solid base substrate. Unlike traditional disposable ‘wet’ gelled Ag/AgCl ECG surface electrodes, which can be uncomfortable and irritating due to their metal-based composition, the proposed electrodes are reusable, non-discomforting, and suitable for long-term cardiac monitoring. Electrophoretic deposition (EPD) technique was utilised to fabricate the Graphite MWCNT hybrid ECG (GCHE) electrodes. To reduce the possible toxicity of dispersants, biocompatible surfactants were employed to disperse the MWCNT on to graphite base material. Analysis was performed to determine the electrochemical properties by using electrochemical impedance spectroscopy (EIS) method and ECG responses for bio-signalling properties. The hybrid structure of electrode ensured signal conductivity, reduced artifacts, and allowed stable bio-signal acquisition. Being all-carbon based ECG surface electrodes offers low toxicity & skin irritation, presenting a promising solution for long-term ECG monitoring and wear ability in healthcare system.

Keywords: Biosurfactants, Carbon nanotube, Electrocardiography, Electrodes

Electrophysiological signals, such as ECG, EEG, EMG, and EOG, require surface electrodes for non-invasive diagnosis¹. Among non-communicable diseases, cardiovascular ailments contribute significantly to the global disease burden, often due to modern lifestyle factors. Consequently, continuous monitoring is crucial for the early detection of symptoms, especially outside clinical settings, to prevent adverse health events². The use of wearable devices equipped with electrodes or sensors has made them crucial for health monitoring. The ECG surface electrode serves as the primary interface between the body and the ECG machine¹. The gold standard in this domain remains the disposable Ag/AgCl electrodes, valued for their affordability and proven reliability over time. However, these electrodes come with certain drawbacks—they are wet-gel-based, uncomfortable for long-term use, and prone to inconsistent readings due to gel drying or motion artifacts during diagnosis^{1,2}.

In recent years, researchers have explored various designs and materials for non-invasive ECG electrodes as alternatives to Ag/AgCl-based wet gel electrodes.

Ideal electrodes must meet criteria such as reliable signal quality, long-term wear ability, reusability, body-conforming contact, reduced motion artifacts, support for remote monitoring, and affordability^{2,3}. Traditional materials like metals (Ag, Au,) have been commonly used for their conductivity, but they face limitations like corrosion and the need for wet gels³.

Non-metallic materials, particularly carbon-based ones like carbon nanotubes (CNTs), have garnered significant attention due to their exceptional electrical, mechanical, and thermal properties. Types of CNTs namely, SWCNT, MWCNT have been tried as a surface electrode (‘forest/brush’ type) for electrophysiological use⁴. The multi-walled carbon nanotubes (MWCNT), in particular, have been used to fabricate surface electrodes for diagnostic monitoring due to their physical properties, low relative toxicity, low-cost affordability⁷. These types of electrodes have been fabricated on metals - Cu, Au, Pt^{5,6}, textile wearable fabrics¹⁵, and polymers^{16,19} as a base for hybrid electrode material. A true “forest” type CNT electrode to fabricate, use, and maintain is inviable due to a lack of present-day techniques and is rarely tried for bioelectrical usage⁷⁻⁹.

Graphite is an allotropic form of carbon. It has electrically conductive properties due to its delocalized

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electron & C-C sp² hybridization structure⁶. In engineering practices, it is used extensively due to its unique chemical and physical characters^{26,27}. There are many graphitic carbon-like materials studied for ECG electrodes, including graphene, rGO, GO, & Super B carbon black¹⁰⁻¹⁴. In light of the versatile nature of carbon and its compounds, and the principles of biomimetics, utilizing a graphite solid base substrate and MWCNT for the ECG surface electrode helps solve many issues¹⁷.

The methods available for depositing MWCNT on other materials (metals, carbon, textiles, and polymers) include drop casting, printing, and compositing^{18,19}. In this study, we employed electrophoretic deposition (EPD) to coat MWCNTs onto graphite-based electrodes. The EPD approach produces relatively stable, uniform electrode material. In the EPD process, the real challenge is to stably disperse MWCNTs, which agglomerate easily²⁰. Although different solvents have been evaluated for dispersing MWCNT, it is crucial to use a non-toxic solvent such as water for ECG studies²¹.

Given the intrinsic hydrophobic nature of multi-walled carbon nanotubes (MWCNTs), the use of biocompatible surfactants, Cetyltrimethylammonium bromide (CTAB) and sodium cocoyl glutamate (Na-CGN) were explored, to enhance their dispersion in water²¹⁻²⁴. These surfactants, chosen for their charged properties, facilitated effective MWCNT deposition and enhanced the electrode's performance in wearable health systems²⁴. The Graphite MWCNT hybrid ECG electrode was evaluated and characterized for electrochemical properties²⁵⁻²⁸ and electrophysiological signalling metrics^{4,7}. The cytotoxic effect of the Graphite MWCNT hybrid ECG electrode was assessed for usability²⁹.

Materials and Methods

The fabrication of graphite electrode base substrate

To fabricate the ECG electrodes, graphite rods (Merck KGaA, Germany) with 99% purity and a 1 cm diameter were machined to the required dimensions (as shown in Fig. 1A & B) using CNC lathe facilities. The dimensions were designed to match the base of disposable Ag/AgCl ECG electrodes¹⁻³. After machining, the graphite rods underwent gasification at 850°C with steam for 1 h to form a porous structure. The rods were then thoroughly cleaned with alcohol and distilled water, followed by drying in a hot air oven at 110°C for 1.5 h^{6,7}.

Coating of MWCNT on graphite substrate using electrophoretic deposition (EPD) Technique

For the MWCNT coating, multi-walled carbon nanotubes (SAT Nano Tech, China) with 99% purity and a 50-90 nm diameter were used. The coating was achieved through the electrophoretic deposition (EPD) technique. To disperse MWCNTs (1.5 mg) in an aqueous medium, the nanotubes were subjected to sonication in an ultrasonic bath for 30 min at 25°C, using biocompatible surfactant solutions²¹. Two surfactants were studied: (a) cetyltrimethylammonium bromide (CTAB, Merck, 90 mg/100 mL) and (b) sodium cocoyl glutamate (Na-CGN, Fengchen Co, China, 87.3 mg/100 mL)^{22,23}. The mixture was centrifuged at 1200 rpm for 20 min to remove any agglomerates, and the supernatant was used for further studies²⁰.

For the EPD process, the machined graphite base substrates were used as the working electrode and immersed in the MWCNT-surfactant suspension, maintaining an equidistance (≈ 2 cm) from a counter electrode made of SS304 stainless steel. A precision DC power supply (Tarson Inc, 0-300V/0.4-5A) provided a 15V supply for 5 min. The entire setup was stirred at 220 rpm using a magnetic stirrer (IKA C-MAG model) to ensure uniform deposition²⁰. After coating, the graphite articles were washed in double-distilled water for 1 h to remove residual

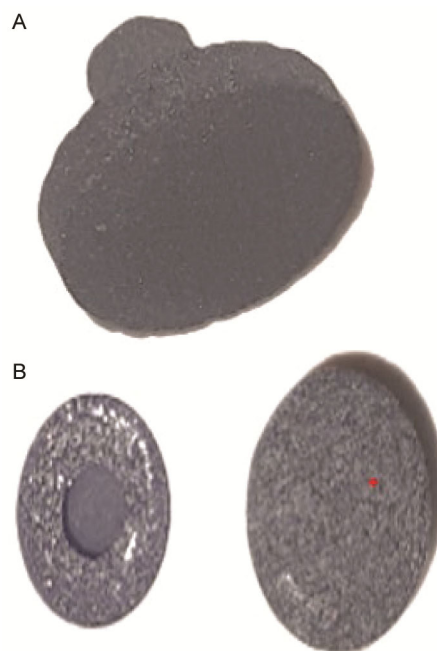


Fig 1 — (A) Machined graphite base substrate (sized 0.8 cm diameter); and (B) Machined graphite base with front and rear-view shapes

surfactants and dried in a hot air oven at 115°C for 1 h. This coating process was repeated three times per graphite article, with the gravimetric analysis used to validate the EPD process^{21,22}. The above coated MWCNT on graphite solid substrate was referred to as Graphite-MWCNT Hybrid ECG Electrode (GMHE).

Characterization of graphite-MWCNT hybrid electrode

FESEM imagery

The surface morphology of the coated electrodes was analysed using field emission scanning electron microscopy (FESEM) (ZEISS Gemini T Sigma300) with in-lens and SE2 detectors⁷.

Electrochemical characterisation by EIS technique

Electrochemical impedance spectroscopy (EIS) was performed using a BioLogic SP-300 system to characterize the electrochemical properties of the electrodes. The electrolyte used was physiological normal saline (0.9% *w/v* sodium chloride), with a platinum wire as the counter electrode and an Ag/AgCl electrode as the reference²⁶. Electrochemical Impedance Spectroscopy (EIS) was used to evaluate the electrochemical response of both the pristine graphite base and the Graphite-MWCNT hybrid electrodes²⁵⁻²⁸. The working graphite-MWCNT hybrid electrode was placed approximately 3 cm from the other electrodes while recording the EIS response. Three repetitive measurements were conducted for each electrode across a frequency range of 7 kHz to 10 μ Hz. The data was processed using Origin Lab software (Origin2024b) for analysis^{25,27}.

Cytotoxicity Testing

The cytotoxicity of the electrodes was tested using the MTT assay on NHDF (Cat. No. C-14031, Promo Cell GmbH) cell lines²⁹. This assay study was performed as previously described²⁹ using MTT (3-[4, 5-dimethylthiazol-2-yl]-2, 5 diphenyl tetrazolium bromide) (Sigma-Aldrich) and its conversion into formazan crystals by living cells, and the absorbance was measured at 570 nm (Bio-Tek Instruments).

Electrode wearability & ECG Study

To make the electrodes wearable, they were attached to the extruded foam base of commercial Ag/AgCl ECG electrodes, with the gel coating completely removed (Fig. 2A & B). This modification allowed the graphite-MWCNT hybrid ECG (GCHE) electrodes to be securely attached to the body and the ECG machine^{4,7}.

For the ECG testing, a SCHILLER AT-2 model ECG machine was used for 12-lead recordings. Healthy male participants aged 20-60 years provided informed consent, and ECG readings were recorded using both standard Ag/AgCl electrodes (as controls) and the GCHE electrodes⁷. The study was conducted under ethical approval obtained from the institutional Human Ethical and Biosafety Committee before conducting ECG studies.

Results

The electrophoretic deposition (EPD) coating of MWCNT on the graphite base electrode in the fabricated graphite-MWCNT hybrid ECG (GCHE) electrodes was confirmed through field emission scanning electron microscopy (FESEM) analysis. Figure 3A shows the pristine graphite base electrode material, while (Fig. 3B & C) illustrate the EPD of MWCNT on the graphite base using the surfactants Cetyltrimethylammonium bromide (CTAB) and Sodium Cocoyl Glutamate, respectively.

Uniform coating of MWCNT on graphite base electrodes by the electrophoretic deposition (EPD) technique was validated with gravimetric analysis (Table 1).

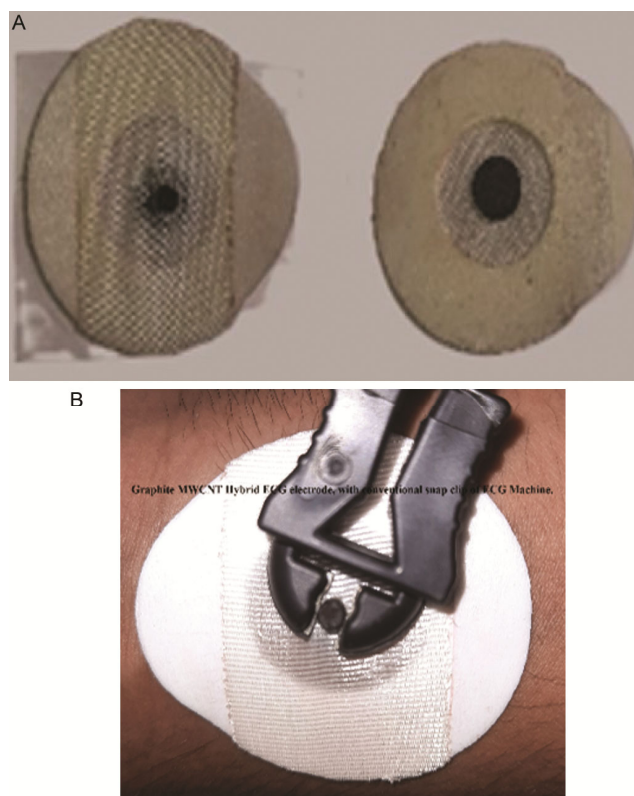


Fig 2 — (A) Front and rear view of Graphite MWCNT hybrid ECG electrode without 'wet' gel filling; and (B) Graphite MWCNT hybrid ECG electrode with snap clip attached for ECG recording

Table 1 — Comparative analysis of fabricated electrodes with reference and blank

Sl. No.	Electrode	Dimension Thickness (cm)	Electrode Inference
1.	Pristine Graphite	≈ 0.8	Blank
2.	Graphite-MWCNT hybrid (CTAB)	≈ 0.8	Working
3.	Graphite-MWCNT hybrid (Na-CGN)	≈ 0.8	Working
4.	Commercial Ag/AgCl disposable	≈ 1.0	Reference

Electrochemical impedance spectroscopy (EIS) was conducted using a BioLogic SP-300 system with normal saline as the electrolyte. The graphite-MWCNT hybrid electrode served as the working electrode spaced 3 cm from the platinum counter and Ag/AgCl reference electrodes. EIS data was collected across 7 kHz to 10 μ Hz and analysed with Origin Lab software. Figure 4A displays the Bode plot between the magnitude of impedance and frequency for the pristine graphite, GCHE-CTAB, and GCHE-Na Cocoyl

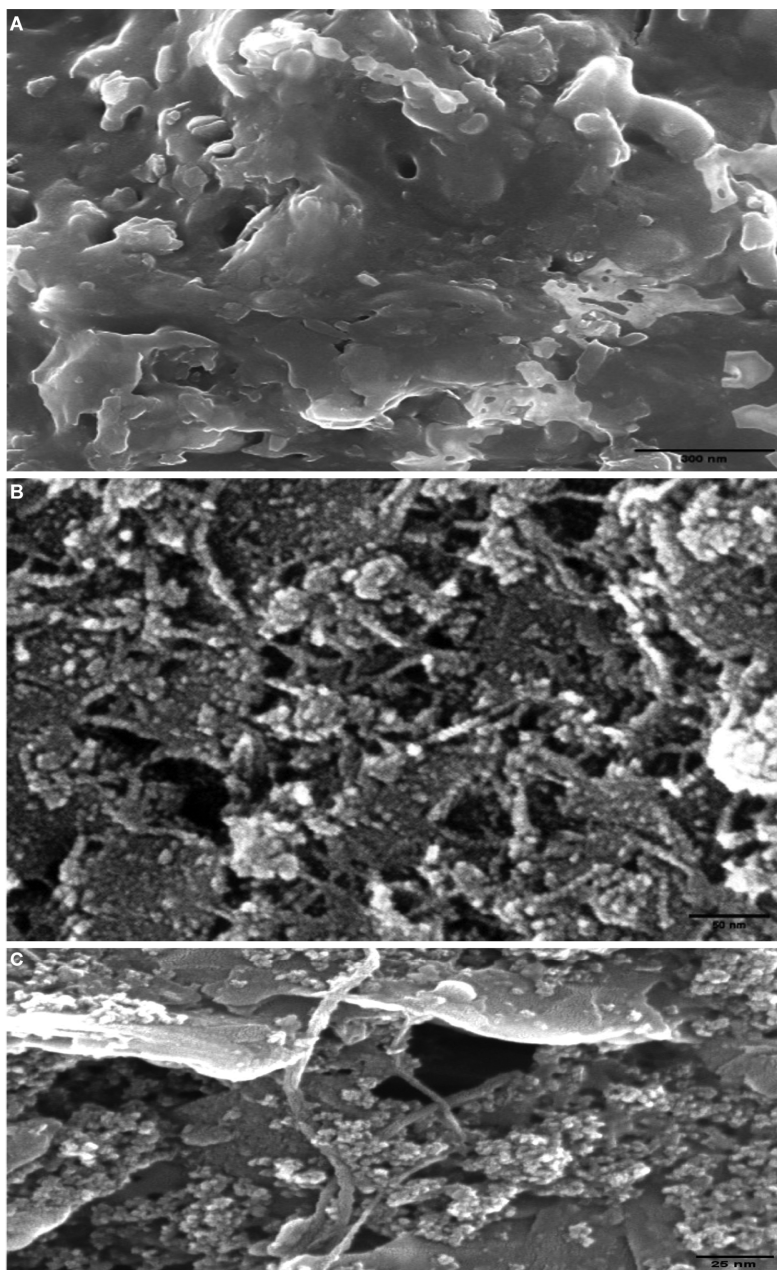


Fig 3 — (A) FESEM image of Pristine Graphite base; (B) FESEM image of Graphite MWCNT Hybrid electrode with CTAB surfactant; and (C) FESEM Image of Graphite MWCNT Hybrid electrode with Sodium Cocoyl Glutamate surfactant

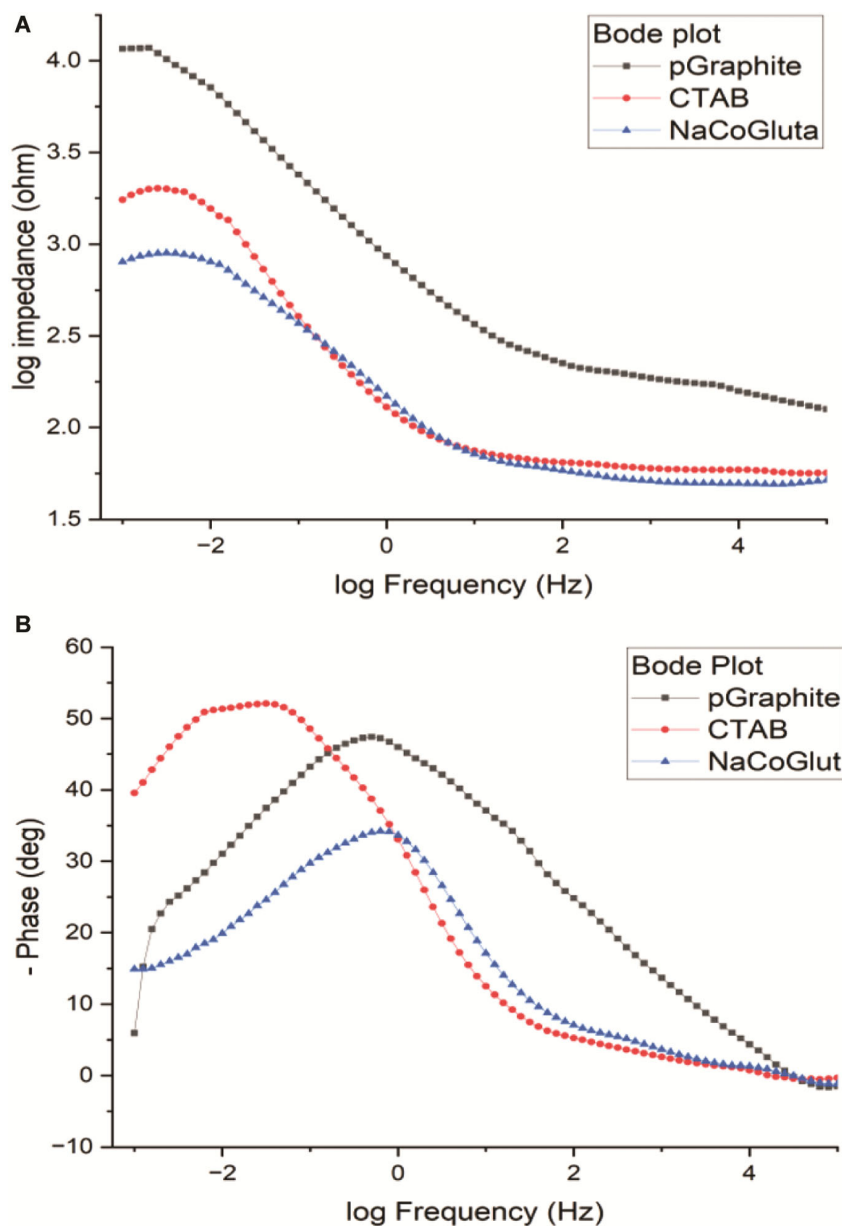


Fig 4 — (A) Bode plot between the magnitude of impedance vs frequency of pristine graphite, GCHE-CTAB, and GCHE--Na Co Glutamate electrodes; and (B) Bode plot between the phase vs frequency of pristine graphite, GCHE-CTAB, and GCHE--Na Co Glutamate electrodes

Glutamate electrodes. Whereas, Figure 4B shows the phase vs frequency plot for the same electrodes. These results reveal that the MWCNT coatings with surfactants significantly affected the impedance characteristics, indicating suitable electrochemical performance. Notably, the cationic CTAB surfactant showed a distinct impedance pattern compared to the anionic Na-CGN, correlating with the charged nature of these surfactants.

The ECG signal responses of the electrodes were also compared. Figure 5 shows the resting ECG signal

recordings for (A) commercial Ag/AgCl electrodes, (B) pristine graphite electrodes, and (C) GCHE electrodes. The GCHE electrodes, both CTAB and Na-CGN dispersant types, showed comparable results to the standard Ag/AgCl electrodes in terms of signal clarity and quality, making them promising alternatives for long-term use in the healthcare industry.

The MTT cytotoxicity test of the Graphite-MWCNT hybrid electrode material using the NHDF cell line showed no significant cytotoxic response.

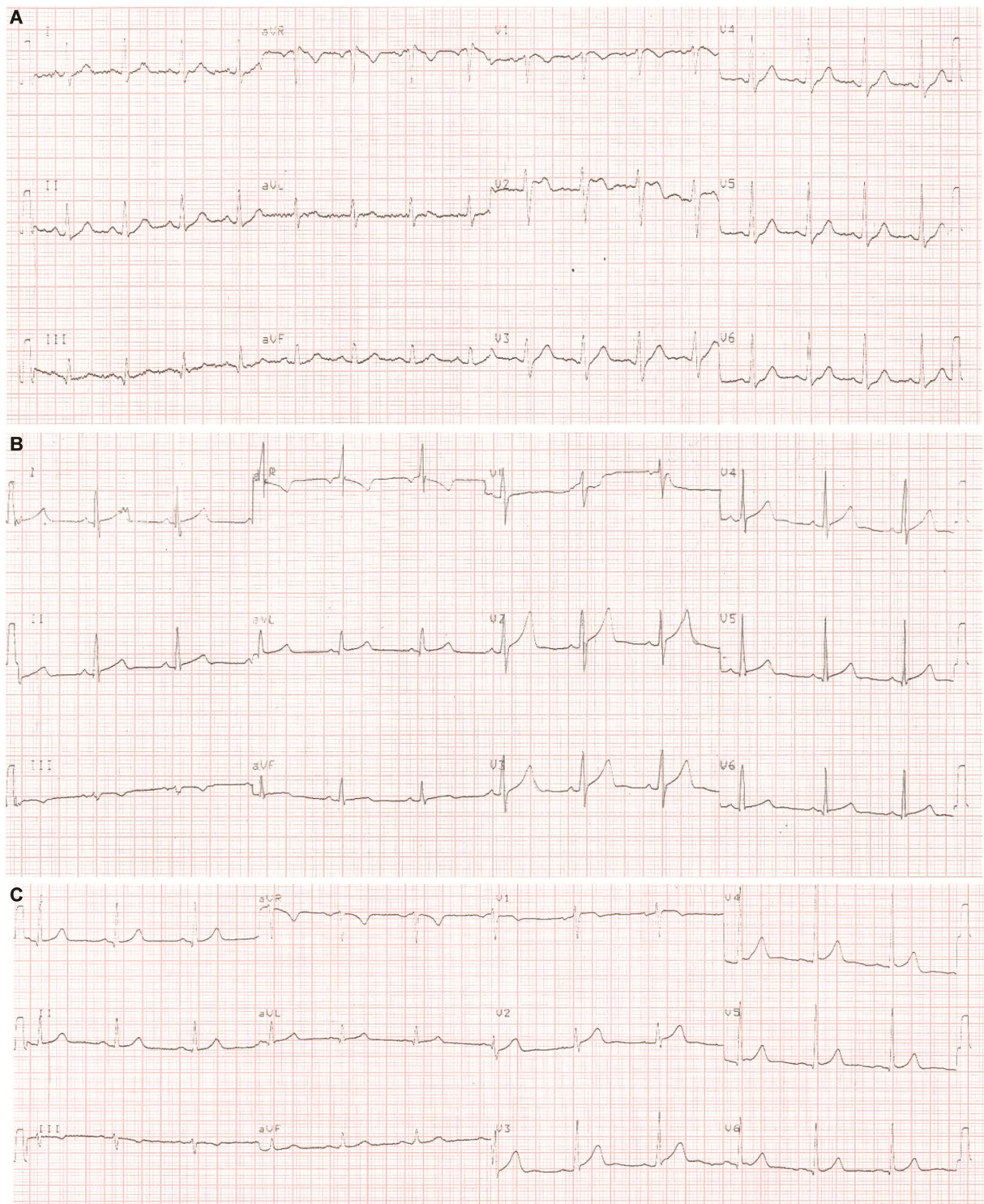


Fig 5 — (A) ECG signal response of Commercial Ag/AgCl ECG electrode; (B) ECG signal response of Pristine Graphite base electrode; and (C) ECG signal response of Graphite-MWCNT Hybrid ECG electrode

Both blank and test samples were evaluated for biocompatibility before conducting participant-level ECG studies, confirming the electrode's safety for biomedical applications. Figure 6 displays the MTT

test results, showing the compatibility of the Graphite-MWCNT hybrid electrodes, indicating their safety for long-term application in wearable health systems.

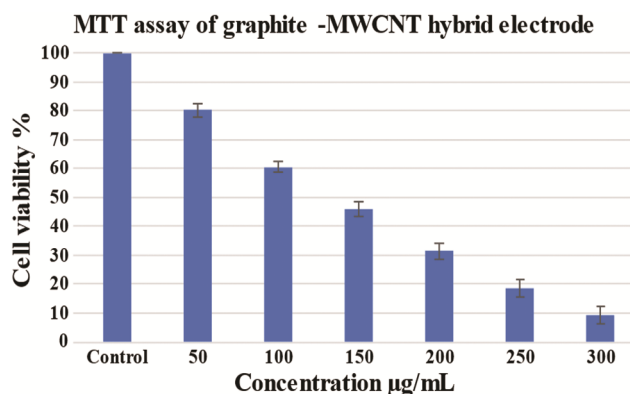


Fig 6 — Cytotoxicity test by MTT Assay of the Graphite-MWCNT hybrid ECG electrode

Discussion

The electrophoretic deposition (EPD) of MWCNTs on the graphite substrate, validated through field emission scanning electron microscopy (FESEM), confirmed the creation of a hierarchical carbon structure. This architecture, with its porous and conductive nature, effectively facilitates signal transmission, as supported by electrochemical and bioelectrical analyses. The hierarchical surface morphology observed in this study is consistent with previous reports on carbon-based electrodes. Studies have established that a structured surface, such as those observed in graphene or single-walled carbon nanotube (SWCNT) composites, significantly enhances electrochemical activity and signal transmission³⁰. Prior studies have reported that hierarchical structures improved electrode performance by increasing active surface area and conductivity³¹. Similarly, in the present work, the sparse but uniform distribution of MWCNTs, facilitated by surfactants CTAB (cationic) and Na-CGN (anionic), underscores a critical improvement in deposition control, which is less emphasized in prior research. This control ensures uniformity and consistency in electrochemical behaviour, critical for reliable signal detection.

Electrochemical impedance spectroscopy (EIS) revealed a distinct impact of surfactant type on electrode behaviour. Bode plots highlighted the modulation of impedance profiles by the charged nature of CTAB and Na-CGN, aligning with earlier studies on surfactant influence in carbon-based composites^{32,33}. This study extends these findings by linking the surfactant-modulated impedance characteristics to practical outcomes in ECG signal quality, offering a more comprehensive understanding of the electrochemical performance.

The comparison of ECG signal recordings from the Graphite-MWCNT hybrid electrodes with commercial Ag/AgCl electrodes represents a significant leap forward in wearable health technology. While Ag/AgCl electrodes remain the gold standard, their inherent limitations, such as drying and motion artifacts, make them less suitable for long-term monitoring^{2,3}. Previous studies explored alternative materials and techniques but often struggled to match the signal fidelity of Ag/AgCl electrodes^{2,7}. Our study demonstrates that the MWCNT-coated graphite electrodes achieve comparable signal quality and also offer durability for extended use, addressing a critical gap in wearable health monitoring devices.

Biocompatibility is a key consideration for wearable devices, and the cytotoxicity testing conducted via the MTT assay in this study confirmed the safety of the graphite-MWCNT hybrid electrodes. The findings align with prior research, which emphasized the role of surfactant stabilization in reducing the cytotoxic effects of carbon nanomaterials³⁴. The minimal cytotoxic response observed here positions these electrodes as suitable candidates for long-term skin contact applications, paving the way for their adoption in non-invasive health monitoring.

The present study demonstrates significant advancements in the development of multi-walled carbon nanotube (MWCNT) -coated graphite electrodes for bioelectrical signal monitoring, particularly in wearable ECG applications. It highlights the potential of combining graphite and MWCNTs with biocompatible surfactants to create advanced dry-type electrodes for ECG monitoring. By overcoming the limitations of traditional wet-gel electrodes and addressing concerns around biocompatibility, this approach offers a transformative solution for wearable healthcare technologies.

Conclusion

Non-invasive biomedical diagnostic techniques, such as ECG, rely on surface electrodes that need to be biocompatible, conductive, and suitable for long-term wear. This study demonstrated that a hybrid graphite-MWCNT electrode, fabricated using electrophoretic deposition and biocompatible surfactants, can serve as a promising alternative to traditional Ag/AgCl electrodes. The findings demonstrate that the electrochemical response and bioelectrical signalling of these electrodes are significantly influenced by the use of charged

surfactants such as sodium cocoyl glutamate and CTAB. The electrodes exhibited good signal transmission, were comparable to commercial electrodes in terms of ECG signal quality, and were low in cytotoxicity. The dry nature of the electrodes further enhances their suitability for wearable health monitoring applications. Future research should focus on refining the EPD technique, exploring different surfactants, and enhancing the durability and sensitivity of the electrodes. The potential for integrating these electrodes into wearable devices is vast, especially in long-term health monitoring and telemedicine, where reliable and comfortable biocompatible electrodes are essential.

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Conflict of interest

All authors declare no conflict of interest.

References

- Kim H, Kim E, Choi C & Yeo WH, Advances in Soft and Dry Electrodes for Wearable Health Monitoring Devices. *Micromachines*, 13 (2022) 629.
- Yao S & Zhu Y, Nanomaterial-enabled dry electrodes for electrophysiological sensing: A review. *JOM*, 68 (2016) 1145.
- Niu X, Gao X, Liu Y & Liu H, Surface bioelectric dry Electrodes: A review. *Meas*, 183 (2021) 109774.
- Gandhi B & Raghava NS, Fabrication techniques for carbon nanotubes-based ECG electrodes: a review. *IETE J Res*, 71 (2020) 24.
- Burbles N, Schulze J, Schwarz HC, Kranz K, Motz D, Vogt C, Lenarz T, Warnecke A & Behrens P, Coatings of different carbon nanotubes on platinum electrodes for neuronal devices: Preparation, cytocompatibility and interaction with spiral ganglion cells. *PLoS One*, 11 (2016) e0158571.
- Jang LW, Shim J, Son DI, Cho H, Zhang L, Zhang J, Menghini M, Locquet JP & Seo JW, Simultaneous growth of three-dimensional carbon nanotubes and ultrathin graphite networks on copper. *Sci Rep*, 9 (2019) 12344.
- Kolanowska A, Herman AP, Jędrzyński RG & Boncel S, Carbon nanotube materials for electrocardiography. *RSC Adv*, 11 (2021) 3020.
- Panchal J, Singh MI, Sandha KS & Singh M, Rapid Fabrication Technique for Dry Electrocardiography Electrodes Using Carbon Nanotube/Polydimethylsiloxane Composite. *J Electron Mater*, 53 (2024) 2633.
- Jung HC, Moon JH, Baek DH, Lee JH, Choi YY, Hong JS & Lee SH, CNT/PDMS composite flexible dry electrodes for long-term ECG monitoring. *IEEE Trans Biomed Eng*, 59 (2012) 1472.
- Lou C, Li R, Li Z, Liang T, Wei Z, Run M, Yan X & Liu X, Flexible graphene electrodes for prolonged dynamic ECG monitoring. *Sensors*, 16 (2016) 1833.
- Dey R, Samanta PK, Chokda RP, De BP, Appasani B, Srinivasulu A & Philibert N, Graphene-based electrodes for ECG signal monitoring: Fabrication methodologies, challenges and future directions. *Cogent Eng*, 10 (2023) 2246750.
- Butt M, Abbod M, Vehkaoja A & Balachandran W, Graphene sensor for smart phone based continuous monitoring of ECG signals. *Biomed Res Clin Pract*, 4 (2019) 1000181.
- Romero FJ, Castillo E, Rivadeneyra A, Toral-Lopez A, Becherer M, Ruiz FG, Rodriguez N & Morales DP, Inexpensive and flexible nanographene-based electrodes for ubiquitous electrocardiogram monitoring. *NPJ Flex Electron*, 3 (2019) 12.
- Noh Y, Bales JR, Reyes BA, Mollignano J, Clement AL, Pins GD, Florian JP & Chon KH, Novel conductive carbon black and polydimethylsiloxane ECG electrode: A comparison with commercial electrodes in fresh, chlorinated, and salt water. *Ann Biomed Eng*, 44 (2016) 2464.
- Alizadeh-Meghrizi M, Ying B, Schlums A, Lam E, Eskandarian L, Abbas F, Sidhu G, Mahnam A, Moineau B & Popovic MR, Evaluation of dry textile electrodes for long-term electrocardiographic monitoring. *Biomed Eng Online*, 20 (2021) 68.
- Abu-Saude M & Morshed BI, Characterization of a novel polypyrrole (PPy) conductive polymer coated patterned vertical CNT (pvCNT) dry ECG electrode. *Chemosensors*, 6 (2018) 27.
- Kumar, S, Sidhu, HK, Paul AK, Bhardwaj N, Thakur NS & Deep A, Bioengineered multi-walled carbon nanotube (MWCNT) based biosensors and applications thereof. *Sens Diagn*, 2 (2023) 1390.
- Posada-Quintero HF, Reyes BA, Burnham K, Pennace J & Chon KH, Low impedance carbon adhesive electrodes with long shelf life. *Ann Biomed Eng*, 43 (2015) 2374.
- Prima JO, Pamungkas B, Nugraha & Suprijanto, Polyaniline as Novel Polymer Materials for Dry Electrode-Based Electrocardiography (ECG). *J Elektron Telekom*, 18 (2018) 1.
- Rehman MAU, Chen Q, Braem A, Shaffer MSP & Boccaccini AR, Electrophoretic deposition of carbon nanotubes: recent progress and remaining challenges. *Int Mater Rev*, 66 (2020) 533.
- Mohan H, Bartkowski M & Giordani S, Biocompatible dispersants for carbon nanomaterials. *Appl Sci*, 11 (2021) 10565.
- Ostos FJ, Lebrón JA, Moyá ML, Bernal E, Flores A, Lépori C, Maestre A, Sánchez F, López-Cornejo P & Lopez-López M, Potentiometric study of carbon nanotube/surfactant interactions by ion-selective electrodes. driving forces in the adsorption and dispersion processes. *Int J Mol Sci*, 22 (2021) 826.
- Okasaka M, Kubota K, Yamasaki E, Yang J & Takata S, Evaluation of anionic surfactants effects on the skin barrier function based of skin permeability. *Pharm Dev Technol*, 24 (2019) 99.
- Corazza M, Lauriola MM, Bianchi A, Zappaterra M & Virgili A, Irritant and Sensitizing Potential of Eight Surfactants Commonly Used in Skin Cleansers: An Evaluation of 105 Patients. *Dermatitis*, 21 (2010) 262.
- Goyal, K, Borkholder DA & Day SW, Dependence of skin-electrode contact impedance on material and skin hydration. *Sensors*, 22 (2022) 8510.
- Wang L, Zhao J, He X, Ren J, Zhao H, Gao J, Li J, Wan C & Jiang C, Investigation of modified nature graphite anodes by electrochemical impedance spectroscopy. *Int J Electrochem Sci*, 7 (2012) 554.

- 27 Yavarinasab A, Abedini M, Tahmooressi H, Janfaza S, Tasnim N & Hoorfar M, Potentiodynamic electrochemical impedance spectroscopy of polyaniline-modified pencil graphite electrodes for selective detection of biochemical trace elements. *Polymers*, 14 (2022) 31.
- 28 Gkaravela A, Vareli I, Bekas DG, Barkoula, NM & Paipetis AS, The use of electrochemical impedance spectroscopy as a tool for the in-situ monitoring and characterization of carbon nanotube aqueous dispersions. *Nanomaterials*, 12 (2022) 4427.
- 29 Chetyrkina MR, Fedorov FS & Nasibulin AG, In vitro toxicity of carbon nanotubes: A systematic review. *RSC Adv*, 12 (2022) 16235.
- 30 Zhang J, Bokov AA, Gao SL, Zhang N, Zhuang J, Ren W & Ye ZG, Effect of hierarchical structure on electrical properties and percolation behavior of multiscale composites modified by carbon nanotube coating. *Compos Sci Technol*, 164 (2018) 160.
- 31 Kamedulski P, Zielinski W, Nowak P, Lukaszewicz JP & Ilnicka A, 3D hierarchical porous hybrid nanostructure of carbon nanotubes and N-doped activated carbon. *Sci Rep*, 10 (2020) 18793.
- 32 Ostos FJ, Lebrón JA, Moyá, ML, Bernal E, Flores A, Lépori C, Maestre Á, Sánchez F, López-Cornejo P & López-López M, Potentiometric Study of Carbon Nanotube/Surfactant Interactions by Ion-selective Electrodes. Driving Forces in the Adsorption and Dispersion Processes. *Int J Mol Sci*, 22 (2021) 826.
- 33 Mane SM, Teli AM, Beknalkar SA, Patil DR, Shin JC & Lee J, Cationic-Surfactant (CTAB) Assisted Preparation of 2D Graphitic Carbon Nitride (g-C₃N₄) Sheets Advances Supercapacitive Performance. *Crystals*, 14 (2024) 312.
- 34 Dong L, Joseph KL, Witkowski CM & Craig MM, Cytotoxicity of single-walled carbon nanotubes suspended in various surfactants. *Nanotechnology*, 19 (2008) 255702.