DESIGN OF ELECTRICALLY CONDUCTIVE, HIGHLY STRETCHABLE, HYGIENIC ELECTRODES FOR ELECTROTHERAPY

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ABSTRACT

The main objective of this study was to create versatile and wearable electrically conductive electrodes for Transcutaneous Electrical Nerve Stimulation (TENS) application, ensuring they are comfortable by depositing silver particles directly onto the carbon particles imparted rubber electrodes. Scanning Electron Microscopy (SEM) was used to analyze the shape of the deposited silver particles. To enhance the electrode's performance during body movements, the conductive fabrics were stretched repeatedly, and changes in resistivity were observed. The electrical resistance showed minimal variation with small extensions, remaining relatively constant between 0–75% stretch. Resistance increased significantly after 80% stretch, but the fabric's resistivity remained stable even after over 100 stretching cycles. Additionally, there was no significant change in resistivity over time at a constant current. The study also investigated the antibacterial properties of the deposited particles against bacteria like Staphylococcus aureus and Escherichia coli. The antifungal activity assessment using Aspergillus fumigatus further underscores the benefits of the silver-plated elastomers in combating fungal growth. Finally, the durability of the coated fabrics concerning comfort and electrical properties was evaluated through multiple pressure applied, showing good particle retention and only a slight decrease in conductivity.

KEYWORDS

Silver electroplating; Carbon particles; Multifunctional electrodes; Electrostimulation and Antibacterial.

INTRODUCTION

The design of electrically conductive, highly stretchable, and hygienic electrodes for electrotherapy is crucial in advancing therapeutic effectiveness and patient comfort. Electrotherapy relies on the precise delivery of electrical currents to stimulate muscles, manage pain, and promote healing, making the quality and functionality of electrodes a key factor in treatment outcomes [1]. Traditional electrodes often face challenges in maintaining conductivity and comfort during dynamic movements, as they may lack flexibility or introduce hygiene concerns with prolonged use. The use of electrotherapy, specifically Transcutaneous Electrical Nerve Stimulation (TENS), in physiotherapy and rehabilitation to manage pain and improve mobility. TENS therapy involves applying electric current to stimulate body nerves, typically using conductive hydrogel electrodes. While self-adhesive hydrogel electrodes are commonly used for TENS, they have drawbacks like discomfort, skin irritations, and hygiene issues [2]. Other types of electrodes, such as carbon rubber electrodes or metal plates covered with nonconductive fabric, have also been utilized but can pose challenges. Despite these challenges, the use of electrodes remains prevalent in TENS applications [3]. To address these limitations, modern electrode designs focus on creating materials that are both electrically conductive and capable of enduring high levels of stretch without compromising performance. Additionally, incorporating antimicrobial and biocompatible properties supports hygiene and skin safety, especially in extended or repeated therapy sessions. In this research, a unique substrate made of cotton, nylon, and lycra was chosen, and a special method for depositing silver nanoparticles onto fibers and within fabric structures was developed. This approach resulted in the creation of conductive fabric-based electrodes with excellent conductivity, flexibility, and stretchability to ensure comfort during use. The study also explored changes in electrical conductivity with repeated stretching to enhance the adaptability of carbon embedded silver plated electrodes for human body movements during electrotherapy sessions [4]. Additionally, these electrodes demonstrated good washing durability, resistance to cracking when stretched, and exhibited

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qualities like drape, softness, and a comfortable feel. The electrodes were engineered by directly plating of very fine silver nanoparticles on them. These electrodes significantly reduced the risk of contact dermatitis and can be safely applied to wounded or injured skin due to the antibacterial and hygienic properties conferred by the silver nanoparticles in the developed carbon embedded rubber electrodes [5].

EXPERIMENTAL AND CHARACTERIZATIONS

Reagent grade chemicals were obtained from sigma Aldrich. Silver nitrate ($AgNO_3$), methanol (99.8%), and calcium carbonate (≥99%) were pur-chased from Sigma-Aldrich. Silicon based elastomers used as matrix in present study weresupplied by R & G Composite Materials (R&G Faserverbundwerkstoffe GmbH), Waldenbuch, Germany. The highly conductive carbonmicroparticles (100 μm) with trade name carbiso mil were obtained from Easy composites, UK. Firstly, 12 of carbon particles were added into methanol solution and then ultrasonicated for 30 min. After ultrasonics 100 mL of silicon elastomer solution was added slowly to the reaction mixture. Then the mixture further ultrasonicated for I hour to produce a conductive elastomer. The methanol was evaporated by placing the beaker in the oven at 55ºC. After the carbon filled elastomers were formed. Subsequently, silver electroplating was done at various time intervals over carbon embedded polymeric rubber. The utilization of SEM and XRD for surface morphology analysis, along with ASTM D257-07 for electrical volume resistivity measurement, indicates a comprehensive approach to characterizing the material properties. Additionally, the Zone of Inhibition test for qualitative measurements and quantitively assessments using AATCC 100-2004 standards, provide valuable insights into the material's antimicrobial properties. Behrens and Karber's technique were used to calculate the virus titer reduction from the basic viral titer of infectivity (107) titer. The plating time and sample codes are given in Table 1 below.

Table 1. Design of experiment of developed samples.

Sr #	Plating Time (min)	Sample code
1	10	S1
2	20	S2
3	30	S3
4	40	S4
5	50	S5
6	60	S6
7	70	S7
8	80	S8
9	90	S9
10	100	S10

RESULTS AND DISCUSSION

Electrical resistivity

Figure 1 is showing the effect of electroplating and weight gain percentage against the electrical resistivity. Increase in electroplating time tends to increase in silver plating and eventually decrease in electrical resistivity values. This trend indicates that optimal electroplating time is essential to achieve low resistivity, as it enhances conductivity by creating a more continuous conductive layer. The weight gain percentage serves as an indicator of the amount of silver coating applied to the electrode, with higher percentages corresponding to increased silver deposition and improved conductivity. The evaluation of the electrical resistivity of the silver-plated samples and the analysis of resistivity at different stretch percentages provide valuable insights into the behavior of the electrodes. The data from Figure 2 showing the resistivity value graphs for each sample is essential for understanding the variations among the samples. The observations regarding resistivity changes at different stretch levels, especially the significant increase in resistivity beyond 75% stretch up to approximately 51 K Ω.mm at 100% stretch, highlight the material's response to mechanical stress. This data suggests that, while silver-plated samples maintain low resistivity under moderate stretch, their conductive performance diminishes significantly under extreme stretching, emphasizing the importance of balancing stretchability and conductivity in electrode design. The durability testing of sample S10, with resistivity measurements at different stretch levels and the calculation of the mean resistivity during one complete cycle, offers a comprehensive assessment of the sample's performance under repeated stretching and release cycles. This detailed analysis is crucial for evaluating the reliability and stability of the electrodes in practical applications. The analysis is critical for applications where electrodes are subject to continuous movement, as it informs decisions about material selection and design parameters that can ensure long-term performance and consistency in electrotherapy applications.

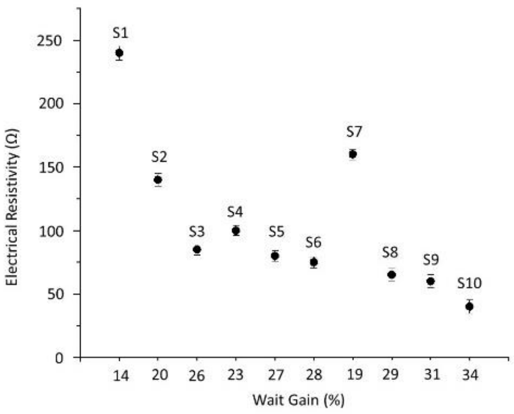

Figure 1. Electrical resistivity at normal stretch.

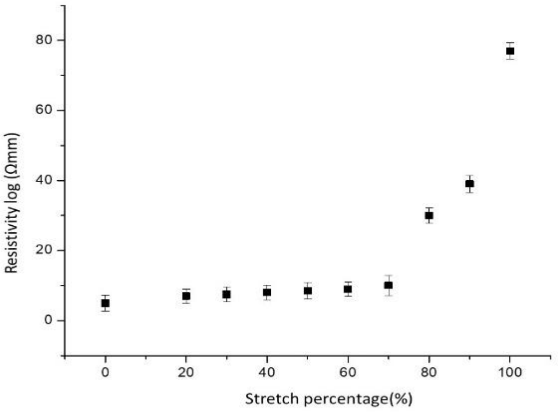

Figure 2. Electrical resistivity at different stretch percentage of Sample 10.

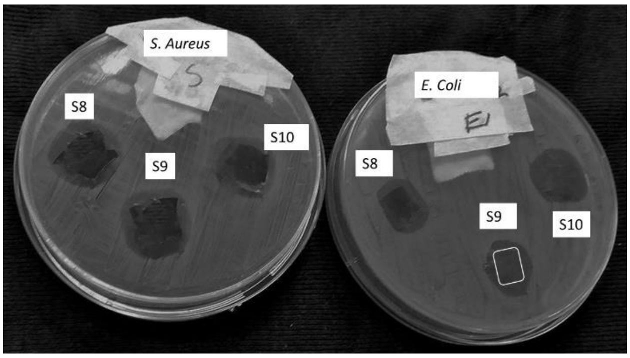

Figure 3. Antibacterial properties with Zone of inhibition.

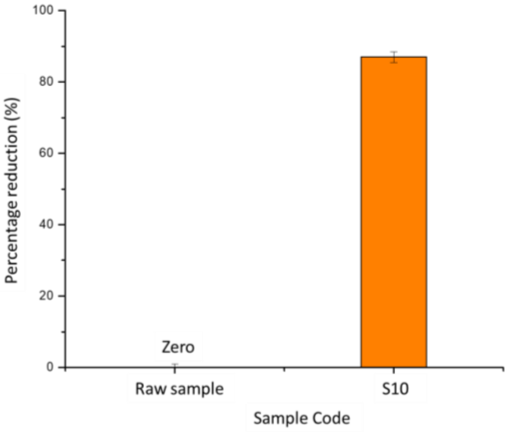

Figure 4. Antifungal activity of silver coated textile.

Antipathogenic properties of developed electrodes

Silver-plated electrodes for Transcutaneous Electrical Nerve Stimulation (TENS) applications are gaining attention not only for their excellent conductivity but also for their inherent antipathogenic properties. Silver is known for its strong antimicrobial effects, which are particularly beneficial in medical and therapeutic devices that come into direct contact with the skin. These properties help reduce the risk of bacterial and fungal contamination, enhancing the hygiene and safety of TENS electrodes used in repeated sessions or extended wear. By incorporating silver plating, TENS electrodes benefit from both improved conductivity and enhanced antipathogenic properties, offering a dual-functionality that aligns with the high standards needed for medical and therapeutic applications. This feature is particularly advantageous in clinical environments and for individuals who use TENS devices frequently, as it contributes to better skin health, reduces maintenance, and extends the electrode's usable life. The Gram-negative *E. coli* and Gram-positive *S. aureus* were used for testing the antibacterial activity of silver-plated elastomers. Figure 3 display the zones of inhibition around the samples after one day of incubation in dark at temperature 37 °C. The results clearly show that the silver coating on the elastomers was effective in creating zones of inhibition against both Staphylococcus aureus and Escherichia coli. The antimicrobial properties of the metal coating, with its unique features like microparticles and biomolecules such as polynuclear acids and proteins, contribute to its effectiveness. This action makes silver-plated electrodes a valuable option for TENS devices, as they can reduce the likelihood of infections and skin irritations often associated with prolonged electrode use. The antibacterial behavior of the silver coating may be due to chemical interactions, physical interactions, or a combination of both, making the prepared electrodes highly hygienic and ideal for hospital environments.

The antifungal activity assessment of silver-plated electrodes for electrotherapy, particularly against *Aspergillus fumigatus*, is an important aspect of ensuring the hygiene and safety of these devices. *Aspergillus fumigatus* is a common fungal pathogen associated with infections, especially on moist skin areas where electrotherapy electrodes are often applied. Silver, known for its broad-spectrum antimicrobial and antifungal properties, releases silver ions that interfere with fungal cell processes, disrupting membrane integrity and inhibiting growth. The antifungal activity assessment using *Aspergillus fumigatus* further underscores the benefits of the silver-plated elastomers in combating fungal growth. Figure 4 display the percentage reduction of fungi (*Aspergillus fumigatus*) with raw sample and samples loaded with silver (87% reduction). Testing silver-plated electrodes against *Aspergillus fumigatus* involves evaluating the fungal inhibition zone or measuring fungal colony counts in the presence of the electrode. Effective antifungal performance would manifest as significant inhibition of *Aspergillus fumigatus* growth around the silver-plated electrode, indicating that the silver ions released are actively preventing fungal proliferation. The silver-plated

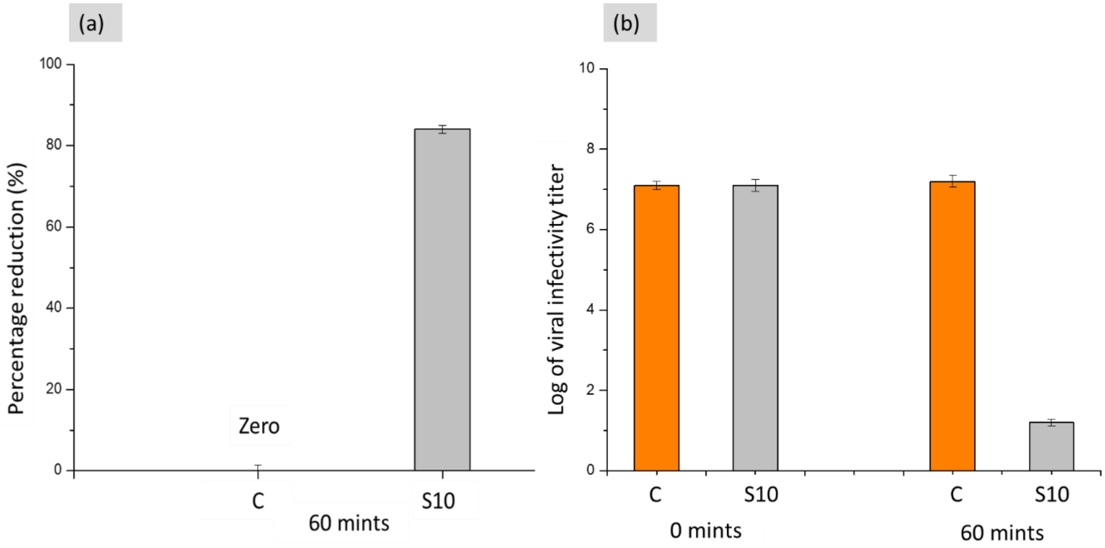

Figure 5. Reduction in viral infectivity titer (a) and percentage reduction (b) calculated from viral infectivity for untreated and treated fabrics at a contact time of 0 and 60 min.

sample exhibit maximum antifungal activity because the metal particles coated elastomer having suitable antibacterial properties. Hence, the percentage reduction of silver nanoparticles greater as compared to phytochemicals. Incorporating silver-plated electrodes with antifungal properties in electrotherapy devices enhances their clinical safety, particularly for patients with extended treatment sessions or sensitive skin.

Figure 5(a) display a graph which shows the virus infectivity titer log against contact time (0 h and 60 mins). Behrens and Karber's method was used for the calculation of virus titers reduction from the starting viral titter of infectivity (107) titer. The Figure 5(a) describes the infectivity titer change of corona virus (0 h and 60 mins) at 25^{o}C for uncoated elastomer and silver coated elastomer S10. It was examined that there is a major decrease in infectivity titer for fabrics coated sample after 60 mins instead of 0 hrs whereas no reduction in virus activity titer was calculated in vase of uncoated elastomer sample. While, Figure 5 (b) exhibit virus percent reduction for uncoated and coated S10 sample. The elastomer treated with silver reduces 84% in virus titer separately uncoated elastomer remained ineffective against virus [6]. The antiviral action exhibited through elastomer treated with silver could be due to the binding of metallic surface with glycoproteins at the viral surface working as an inhibitory action for viruses.

The effect of applied pressure on electrode resistivity during electrotherapy

The applied pressure on electrodes during electrotherapy significantly impacts electrode resistivity, which in turn affects the effectiveness of current delivery to the targeted tissue. When adequate pressure is applied, it improves the contact between the electrode and skin, reducing resistivity and allowing for better current flow. This optimized current distribution enhances the therapeutic benefits of electrotherapy. However, too much or too little pressure can alter resistivity unfavorably, either causing patient discomfort or reducing treatment efficacy. Therefore, controlling applied pressure is essential for achieving consistent and effective results in electrotherapy applications. The high potential signals from the skin are captured using wet and dry electrodes, even when the body is in motion. In our current research, we explored the effects of applying loads of 250g, 500g, and 750g on a 10cm × 10cm sample, which translates to pressures of 4 N/cm^2, 6 N/cm^2, and 8 N/cm^2.The trend line values of electrical resistivities with respective applied pressure are shown in Figure 6. The pressure applied had a significant impact on the electrical resistivity of the electrodes. An evident decrease in resistivity was noted with increasing pressure. Initially, the resistivities of samples S8, S9 and S10 were 62 Ω.mm, 55 Ω.mm, and 24 Ω.mm, respectively. When the pressure reached 6 N/cm^2, the values decreased to approximately 23 Ω.mm, 17 Ω.mm, 14 Ω.mm, and

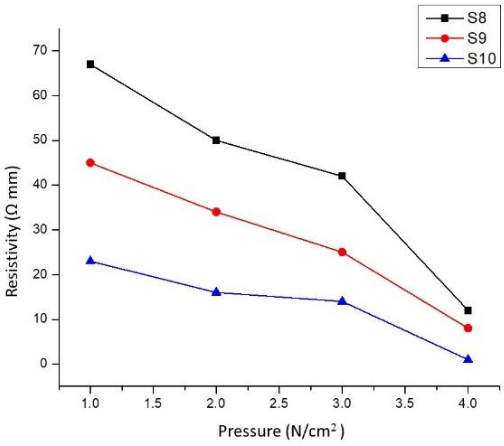

Figure 6. Trend line values of electrical resistivity with respective applied pressure.

1 Ω.mm. A similar approach was taken in a previous study that explored the effect of pressure on dry textile electrodes for obtaining ECG signals. They observed that increased pressure led to lower impedance. Specifically, the impedance decreased as the contact area between the conductive network and skin increased. Since polymers and textiles are soft materials, squeezing them improves the contact interface, resulting in better signal acquisition.

CONCLUSION

The development of those electrically conductive and highly stretchable electrodes for TENS machines sounds really impressive! Achieving a minimum resistivity of 1183 Ω.mm at 12% carbon particles and a volume resistivity of 23 Ω.mm in the conductive elastomer samples is quite remarkable. The fact that these electrodes also demonstrated significant effectiveness against various pathogens in antipathogenic testing is a great advantage. The silver electroplating over the carbon-embedded electrodes seems to have enhanced their properties further. The potential applications of these electrodes in electrostimulation and electrotherapy fields hold a lot of promise for future use. Silver-plated elastomers demonstrated robust antibacterial and antifungal effects, inhibiting bacterial growth (e.g., *E. coli* and *S. aureus*) and fungal pathogens like *Aspergillus fumigatus*. Antiviral tests showed an 84% reduction in viral infectivity after 60 minutes of contact time, making these materials ideal for applications in medical environments. Applying pressure to the electrodes during electrotherapy improved conductivity by reducing resistivity due to enhanced contact with the skin. Increased pressure (up to 8 N/cm²) led to significant resistivity reductions, indicating the importance of optimized contact pressure for effective electrotherapy. These silver-plated elastomers are particularly suited for Transcutaneous Electrical Nerve Stimulation (TENS) devices, offering dual benefits of low resistivity and antimicrobial protection. Their performance under mechanical stress and repeated usage cycles, coupled with their hygienic properties, make them valuable for clinical and home-based therapeutic applications. They are useful for clinical and home-based therapeutic applications because of their ability to withstand mechanical stress and numerous usage cycles as well as their hygienic properties.

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