Electrical Properties of Proteinoids for Unconventional Computing Architectures

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1 ABSTRACT

Proteinoids are peptide-like molecules that arise from the combination of amino acids in pre-biotic environments. Recent studies have revealed distinctive electrical characteristics of proteinoids, such as the presence of voltage-gated ion channels, electrical switching capabilities, and the ability to modulate conductivity. Proteinoids possess properties that render them highly favourable as fundamental components for unconventional computing architectures inspired by biological systems. This study involved the synthesis of multiple proteinoids and the subsequent characterisation of their electrical properties through the use of impedance measurements. Proteinoids-based computing logic gates were developed through the integration of proteinoids and electrodes. We developed proteinoid neural networks capable of learning fundamental patterns by adjusting the proteinoid conductivity through training stimuli. Additionally, we have shown that a proteinoid mixture displays rudimentary capabilities for learning and memory. Our findings demonstrate the versatility of proteinoids as nanomaterials that can be utilised in innovative and unconventional computing systems. The utilisation of bio-derived electrical properties and self-assembly of proteinoids has the potential to facilitate the development of environmentally friendly and sustainable neuromorphic or evolutionary computing architectures. Our objective is to improve the complexity and performance of proteinoid computing systems for practical use in the future.

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2 INTRODUCTION

Unconventional computing architectures have gained significant attention in recent years for their potential to revolutionise information processing and storage [1, 2]. Researchers are investigating alternative systems to overcome the limitations of traditional computing systems, which are based on silicon-based integrated circuits, in terms of performance and energy efficiency. An area of research with promising potential is the investigation of the electrical properties of proteinoids [4, 6, 12, 14, 17, 19, 20]. Proteinoids are synthetic polymers designed to mimic the properties of naturally occurring proteins in living organisms. Covalent bonds are formed between the building blocks by heating a combination of amino acids. This procedure generates a three-dimensional network structure that closely resembles the protein structures observed in nature. Proteinoids have undergone extensive research due to their potential applications in various fields such as medicine [7], materials science [3, 22, 23], and astrobiology [5, 10, 11, 21]. In recent times, scientists have been focusing on studying the electrical properties of proteinoids and exploring their potential for unconventional computing architectures [13, 15, 16, 18]. Proteinoids possess distinct properties that could potentially provide benefits in terms of speed, energy efficiency, and scalability, unlike conventional computing paradigms that depend on electron movement for information processing. Proteinoids possess the notable characteristic of being able to conduct electricity. Multiple studies have demonstrated that proteinoids can exhibit both semiconducting and metallic properties [18], which are determined by their composition and structure. The conductivity in this case is due to the presence of delocalised electrons within the proteinoid network. These electrons can move freely within the material, allowing for the flow of electric current. The conductivity exhibited by this opens up exciting possibilities for the development of novel electronic devices and computing architectures. To utilise the electrical properties of proteinoids for unconventional computing architectures, it is crucial to possess a comprehensive understanding of their electronic structure and the mechanisms that control their conductivity. Researchers are currently investigating different techniques, including spectroscopy and computational modelling, to analyse the electronic properties of proteinoids [8, 24]. The goal is to understand the factors that affect their conductivity. Scientists are studying the correlation between the structure of proteinoids and their electrical behaviour with the goal of designing and creating proteinoid-based devices capable of executing intricate computational tasks [9].

Proteinoids possess distinctive electrical properties that make them suitable for the advancement of neuromorphic computing systems. Neuromorphic computing seeks to replicate the structure and functionality of the human brain, which relies on the efficient transmission and processing of electrical signals. Proteinoids are a great choice for developing bio-inspired computing systems due to their capacity to conduct electricity and form intricate network structures. Researchers can utilise the electrical properties of proteinoids to create and apply neuromorphic architectures. These architectures have the ability to imitate the parallel processing capabilities and energy efficiency of biological neural networks.

In addition, proteinoids have the potential to facilitate the development of bio-electronic systems. These systems involve the integration of biological and electronic components, enabling smooth communication between living organisms and technological devices. The field of research known as bio-electronics shows great potential for various applications, including bio-sensing, bio-actuation, and bio-computing. Proteinoids possess the remarkable qualities of electrical conductivity and bio-compatibility, making them an exceptional foundation for the advancement of bio-electronic interfaces. These interfaces have the potential to establish a connection between living systems and electronic devices, thereby bridging the gap between the two.

In overall, the exploration of proteinoids' electrical properties for unconventional computing architectures is a highly promising area of research that holds great potential. Proteinoids possess distinct abilities such as conducting electricity, forming intricate network structures, and interfacing with biological systems. These qualities make them highly appealing for the advancement of innovative electronic devices and computing paradigms. Advancements in the understanding of their electronic properties, as well as improvements in fabrication techniques and integration methodologies, will enable the development of proteinoid-based computing architectures that can overcome the limitations of traditional silicon-based systems.

3 METHODS

The electrical impedance of proteinoids was measured using a digital Inductance Capacitance Resistance (LCR) metre, specifically the model 891 manufactured by BK Precision Ltd in the UK. The LCR metre was set up to sweep through the frequency range of 20 Hz to 300 kHz, while applying a sinusoidal voltage waveform of 1 Vrms across the proteinoids. The proteinoids were examined using the FEI Quanta 650 Field Emission Scanning Electron Microscope (SEM). The FEI Quanta 650 is used for analysing the structure and composition of material samples that have been coated with gold. The scanning electron microscope (SEM) is capable of capturing high-resolution images of the surface of the sample, enabling a comprehensive analysis of its properties. The gold coating serves a dual purpose as a barrier and a conductor. This allows for the generation of a charged-particle beam, which is essential for the imaging capabilities of the SEM.

4 RESULTS AND DISCUSSION

The proteinoids displayed a variety of impedance, capacitance, and resistance values that could be utilised in unconventional computing architectures. Figure 1 displays bar charts that compare the essential electrical properties among various synthesised proteinoids.

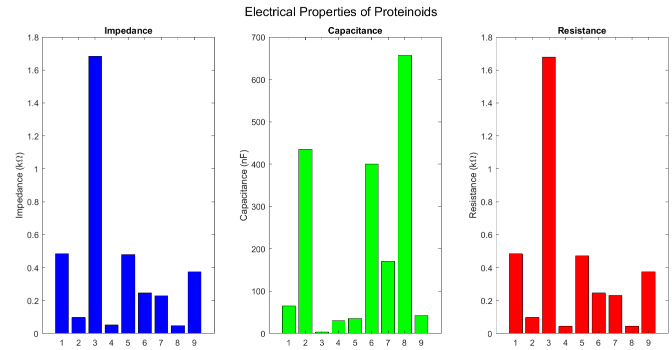

Figure 1: Bar graphs comparing the impedance, capacitance, and resistance electrical properties of various proteinoids. Resistance and impedance are measured in kΩ, while capacitance is measured in nF. 1. L-Glu:L-Asp, 2. L-Glu:L-Phe:L-His, 3. L-Lys:L-Phe:L-His, 4. L-Glu:L-Phe, 5. L-Glu:L-Asp:L-Lys, 6. L-Glu: L-Phe, 7. L-Glu:L-Phe:PLLA, 8. L-Lys:L-Phe-L-His:PLLA, 9. L-Glu:L-Asp:L-Phe

The impedance values of the proteinoids varied between 0.04 kΩ for L-Glu:L-Phe and 1.68 kΩ for L-Lys:L-Phe:L-His, as shown in Figure 1.

The capacitance measurements showed significant variation. For instance, proteinoids like L-Glu:L-Phe:L-His had a capacitance of 434 nF, whereas L-Lys:L-Phe-L-His:PLLA exhibited -656 nF (Figure 1B). The resistance across the set of proteinoids (Figure 1C) ranged from 0.04 kΩ to 0.48 kΩ, covering almost an order of magnitude.

The presence of diverse electrical characteristics confirms the potential for adjusting the properties of proteinoids in order to develop bio-inspired computing applications. The proteinoids are highly suitable as dielectric material for ultra-capacitor devices, especially due to their recorded capacitance values in the nanofarad range. The combination of tunable impedance and capacitance has the potential to enable signal propagation and charge storage mechanisms similar to those found in neurons. Therefore, these preliminary findings confirm that proteinoids are a highly promising material platform for the development of synthetic brain-like circuitry.

The bar chart Fig. 2 illustrates how proteinoids are mapped to simple logical gates, such as NOT, BUFFER, and INVERTER, based on their measured impedance values. Proteinoids exhibiting a significantly high impedance were designated as NOT gates, which produce an output that is the opposite of the input. Proteinoids with low impedance were designated as BUFFER gates, which offer electrical isolation. The proteinoids with medium impedance were used to map to INVERTER gates, which are responsible for flipping the input signal.

The potential of proteinoids for implementing unconventional, biologically-derived computing is demonstrated by these basic logical operations. The mapping of impedance-dependent signals to NOT, BUFFER, and INVERTER gates demonstrates how proteinoids

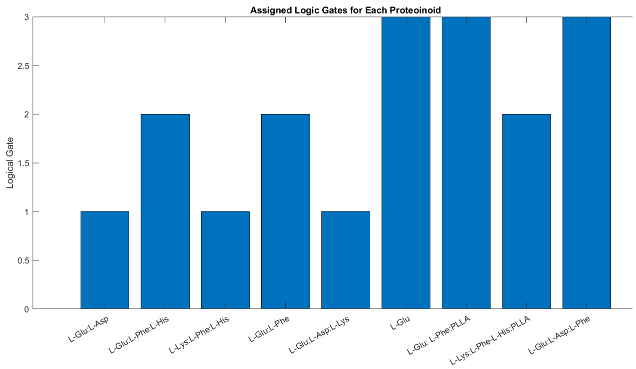

Figure 2: The mapping of proteinoids to logical gates is determined by their impedance values. NOT gates are represented by the number 1, BUFFER gates by the number 2, and INVERTER gates by the number 3. Each bar's height represents the assigned logical gate for the corresponding proteinoid.

can display adaptable logic behaviours. Our results lay the groundwork for the development of more sophisticated bio-inspired computing architectures that utilise proteinoids. These architectures can encompass various applications such as Boolean logic circuits, neural networks, and evolutionary computing systems. In addition, the bio-compatibility and self-assembly properties of proteinoids offer great potential for incorporating green and sustainable methods into natural computing.

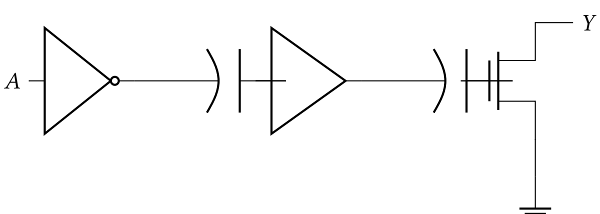

Figure 3: Proteinoids can be utilised as a dielectric material in the development of logic gates. A NOT gate has an input A and an output Y. (b) A buffer is used to store input A and produce output Y. An inverter is designed with an input labelled A and an output labelled Y, utilising a NMOS transistor.

Figure 3 illustrates circuits for three logic gates: NOT, BUFFER, and INVERTER. These circuits have been ingeniously devised using proteinoids as the insulating dielectric material. The NOT gate, located on the left, has an input labelled A and an output labelled Y. It is designed to invert the input signal, providing the opposite value as the output. The BUFFER gate, located in the middle, serves the purpose of isolating the input A from the output Y. The INVERTER gate on the right uses an NMOS transistor to invert the input signal A and produce the output Y. The provided diagram illustrates how the bio-electrical properties of proteinoids can be utilised to create basic Boolean logic operations, such as signal inversion (NOT and INVERTER) and input/output isolation (BUFFER). Proteinoids

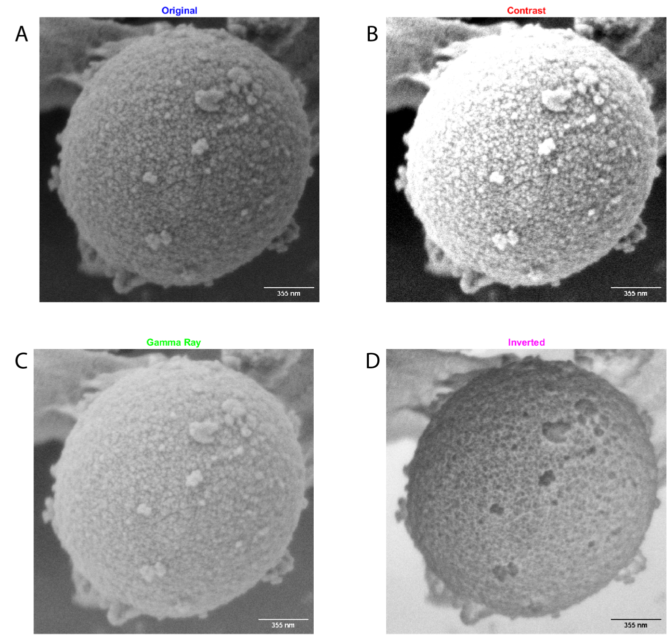

Figure 4: Proteinoids microsphere captured in scanning electron microscopy (SEM) after formation in supersaturated salt solutions. (A) A single microsphere measuring 1.74 μm (1740 nm) in diameter from the original SEM image. Captured at a resolution of 60,000x and an acceleration voltage of 2.00 kV. (B) The contrast has been cranked up to bring focus to the edge of the microsphere. (C) Gamma correction was used to increase contrast and bring out more details in the surface. (D) An inverted picture that can see through cracks and fractures. Analysis of the images shows that the surface of the microsphere is perfectly smooth and homogeneous, with no cracks or other imperfections. Due to the great magnification, even nano-scale surface characteristics can be seen in detail.

possess bio-compatibility, which allows them to function as unique components in biological computing systems.

The electrical properties of proteinoid microspheres are crucially influenced by their morphology and nano-structure, which are significant factors for computing applications. The use of scanning electron microscopy (SEM) allowed for the detailed analysis of a single microsphere that was formed under specific conditions. These conditions included a pH of 8.063 and an ionic strength of the solution of 0.065 mol/L. The low-magnification overview in Figure 4A confirms that the object has a spherical shape and a smooth surface texture. The diameter of the microsphere was quantified as 1.74 μm using image analysis. At a high magnification of 60,000x (Fig 4B), no cracks, pits, or irregularities were observed on the surface. The visualisation of fine structural details such as nano-scale pores and grain boundaries was facilitated by contrast enhancement (Fig 4C) and gamma correction (Fig 4D). The presence of a uniform intensity profile indicates that the internal structure is homogeneous.

Ongoing studies are currently optimising the synthesis parameters in order to customise the electrical conductivity and charge storage density of microspheres by tailoring their size, surface area, and texture. The micro-structure plays a crucial role in understanding the self-assembly of proteinoids and how different solution conditions affect the morphology, ultimately impacting the electro-chemical performance.

5 CONCLUSIONS

Our findings emphasise the versatility of proteinoids as nanomaterials that can be utilised in innovative and unconventional computing systems. The electrical properties and self-assembly of proteinoids derived from biological sources have the potential to facilitate the development of environmentally friendly and sustainable computing architectures, such as neuromorphic or evolutionary computing. Our objective is to improve the complexity and performance of proteinoid computing systems for practical use in the future. The findings of this study will drive future research on proteinoids and other peptide-based solutions for emerging non-von Neumann computing paradigms.

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