Research Article

Polydimethylsiloxane Based Flexible Antenna with Enhanced Performance and High-Efficiency for Biomedical Applications

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Abstract
PDMS is frequently utilized in the biomedical field because of its biocompatibility. The PDMS finds applications in medical implants, cardiovascular flow replication, and in the biomedical industry. This paper presents an innovative antenna design optimized for biomedical applications operating in the Industrial, Scientific, and Medical (ISM) band (2.4–2.5 GHz). The proposed antenna features a compact, flexible structure utilizing a Polydimethylsiloxane (PDMS) substrate to prioritize patient safety and comfort. For PDMS, the loss tangent is 0.0134 and the dielectric constant is 2.71. The design process employs parametric optimization to achieve a low-profile configuration with a wide impedance bandwidth and better radiation characteristics. Simulations and experimental validation using a multi-layered tissue phantom demonstrate superior performance, achieving a return loss below -10 dB across the ISM band. Additionally, Specific Absorption Rate (SAR) measurements confirm compliance with international safety standards, ensuring minimal electromagnetic exposure. PDMS-based flexible antennas hold promise for biomedical applications, but many existing designs face challenges related to limited gain, narrow bandwidth, and poor mechanical stability under continuous body movement. This highlights the need for more reliable and adaptable antenna solutions for on-body use. This study underscores the potential of the proposed ISM-band antenna to enhance the functionality and efficiency of biomedical communication systems, driving advancements in telemedicine and personalized healthcare solutions.

Keywords: Biomedical applications, Flexible antenna, Microstrip patch, Polydimethylsiloxane

1 Introduction

Recent advancements in biomedical technology have led to an increasing demand for highly efficient and reliable wireless communication systems. Antennas play a pivotal role in facilitating effective data transmission for biomedical devices such as implantable sensors, wearable health monitors, and diagnostic tools. These applications require antennas that meet specific criteria, including biocompatibility, flexibility, and compactness. As a result, there has been significant innovation in materials and designs for antenna systems.

Polydimethylsiloxane (PDMS), a biocompatible and flexible silicone-based polymer, has emerged as an ideal substrate material for antenna fabrication [1]. Known for its mechanical robustness, low permittivity, and chemical stability, PDMS is particularly well-suited for wearable and implantable devices. However, working with flexible materials like PDMS presents challenges in achieving optimal performance, especially in terms of efficiency, gain, and radiation characteristics [2].

With the increasing demand for wearable and implantable biomedical devices, the necessity for flexible, efficient, and biocompatible antennas has become more crucial. These antennas are essential for non-invasive monitoring systems used in wireless communication or microwave imaging for diagnosing health conditions. The antennas designed for such biomedical applications must meet stringent requirements such as compact size and flexibility, while ensuring reliable operation in the human body's environment.

PDMS has proven to be a promising material for flexible antenna substrates, offering advantages such as biocompatibility, mechanical flexibility, and ease of fabrication. These properties make PDMS an ideal choice for wearable medical devices, providing a significant advantage over traditional rigid antenna designs [3]. Despite growing research interest, existing antenna designs face several limitations when deployed in on-body environments. Many suffer from narrow bandwidth, low radiation efficiency, and detuning caused by the lossy and high-permittivity nature of human tissues. In addition, mechanical instability under body movement can lead to inconsistent performance, making them less reliable for long-term biomedical use. Prior works have explored various flexible substrates and geometries, but often lack comprehensive evaluation under realistic body conditions or fail to maintain optimal return loss and SAR compliance simultaneously.

To overcome these challenges, this study proposes a novel PDMS-based flexible antenna engineered to operate within the 2.4–2.5 GHz ISM band, a widely used frequency range for biomedical wireless communication. The antenna is parametrically optimized using ANSYS HFSS to ensure a low-profile, wideband, and mechanically robust design. Extensive simulations and validation using multilayer human tissue phantoms demonstrate that the antenna maintains return loss below -10 dB across the ISM band and complies with international SAR safety standards, ensuring safe operation during prolonged on-body use.

The importance of this research lies in addressing the persistent trade-offs between flexibility, electromagnetic performance, and biological safety in antenna design. The proposed antenna contributes toward the realization of durable, efficient, and safe wearable systems for real-time healthcare monitoring and medical diagnostics, offering a significant step forward in personalized healthcare technology.

Flexible and wearable antennas have emerged as a key enabling technology for modern biomedical applications, including health monitoring, diagnostic imaging, and implantable communication systems. These antennas must meet specific requirements such as biocompatibility, mechanical flexibility, compact size, and stable performance in proximity to the human body. Among the various materials explored for such applications, Polydimethylsiloxane (PDMS) has gained significant attention due to its favorable dielectric properties (dielectric constant ≈ 2.71, loss tangent ≈ 0.0134), excellent biocompatibility, and mechanical flexibility.

Amin *et al.*, showcased the potential of flexible PDMS substrates in antenna design, achieving a return loss of -28 dB and a bandwidth of 100 MHz at 2.4 GHz [4]. Likewise, Kumar *et al.*, engineered a PDMS-based antenna tailored for wearable sensor applications at 2.45 GHz, demonstrating a return loss of -35 dB and an efficiency of 85%. These studies underscore the viability of PDMS as a flexible, biocompatible material for biomedical antenna applications [5].

Zhang *et al.*, explored the use of a PDMS-based antenna for medical wireless communication, designed to operate at 2.45 GHz. Their study achieved a gain of 6.5 dB and an impedance bandwidth of 180 MHz [6]. While these studies demonstrated the feasibility of using PDMS for biomedical antenna applications, the performance of the antennas could be further enhanced with improved efficiency, compactness, and better matching for wearable health-monitoring devices.

This paper addresses these challenges by presenting a PDMS-based flexible antenna with enhanced performance for biomedical applications. The proposed antenna design incorporates innovative features to improve efficiency and compactness, making it well-suited for integration into wearable medical systems.

Several studies have explored the integration of flexible substrates for on-body antenna design. For instance, a study by Hussain *et al*., introduced a low-profile polymer-based antenna optimized for broadband and wearable applications; however, issues such as reduced gain and deformation under dynamic movement remained unaddressed. Similarly, Abbas *et al*., explored textile-based antennas but highlighted challenges in achieving stable impedance matching and long-term wearability. Research by Zhu *et al*., demonstrated multilayer phantom-based validation for flexible antennas, but lacked optimization for both mechanical reliability and wideband operation in the ISM band.

Despite these efforts, many existing antenna configurations face challenges related to impedance mismatch, restricted bandwidth, and compromised radiation performance when interfaced with lossy human tissue. The high dielectric contrast between the antenna substrate and body layers can detune the antenna and reduce efficiency. Moreover, limited studies incorporate comprehensive simulation strategies that consider tissue-phantom interaction, specific absorption rate (SAR) compliance, and return loss validation over the target frequency band.

This work addresses these gaps by proposing a novel PDMS-based compact antenna specifically engineered to operate within the 2.4–2.5 GHz ISM band, suitable for diverse biomedical applications such as remote health monitoring and microwave-based imaging. The antenna design uses parametric optimization in ANSYS HFSS to achieve a low-profile structure with a wide impedance bandwidth and enhanced radiation characteristics. The PDMS substrate is selected not only for its mechanical advantages but also for its biocompatibility, enabling safe and long-term contact with skin. Simulations and experimental validations on a multilayer tissue phantom demonstrate consistent performance, including return loss below -10 dB and SAR values within international safety limits. Thus, the proposed antenna contributes to overcoming the trade-offs between flexibility, performance, and safety in biomedical antenna design, offering a promising solution for next-generation wearable and diagnostic devices.

2 Materials and Methods

To improve flexibility in wearable sensor applications, a variety of flexible substrates, such as polyethylene, polyester, and polyamide, are widely used [7]. Among these, polyamide is particularly favoured due to its superior attributes, including waterproofing and rapid drying, which make it more suitable for wearable technologies compared to natural materials like cotton and wool. These properties position polyamide as an optimal substrate for designing and implementing wearable microstrip patch antennas [8], [9].

The designed antenna is built on a polyamide substrate with a dielectric constant of 3.6. It features overall dimensions of 48 × 56 × 1 mm^3, with a 36 × 44 mm^2 radiating patch and a ground plane extending across 48 × 56 mm^2. The design and simulation process are conducted using ANSYS HFSS, a finite element method (FEM)-based software widely employed for electromagnetic analysis.

In the FEM analysis using ANSYS HFSS, various boundary conditions are employed to accurately simulate electromagnetic interactions. A Radiation Boundary (or PML) is used to model open space, preventing wave reflections at the simulation domain's edges. Perfect Electric Conductor (PEC) boundaries are applied to metallic structures, ensuring ideal conductive behavior. Wave Ports serve as excitation sources at feed points, while Symmetry Boundaries reduce computational effort by modeling only half of the structure. For modeling biological tissues, appropriate dielectric material properties and boundary conditions are applied to tissue phantoms, ensuring realistic wave interaction with the human body. These boundary conditions ensure that the simulation accurately reflects the physical behavior of the antenna in its operational environment.

The resonant frequency of an antenna decreases with increasing slot length, allowing for size reduction and frequency tuning. To enhance resonance and radiation performance, the designed antenna incorporates strategically placed slits. The slot dimensions are precisely adjusted to achieve the desired frequency and gain characteristics. A novel design methodology is employed by incorporating slots of varying shapes and dimensions into the patch. The optimized rectangular microstrip patch antenna is engineered to resonate well at 2.45 GHz, ensuring its effectiveness across various applications. The proposed model of antenna, modelled using ANSYS High-Frequency Structure Simulator (HFSS) software, is depicted in Figure 1.

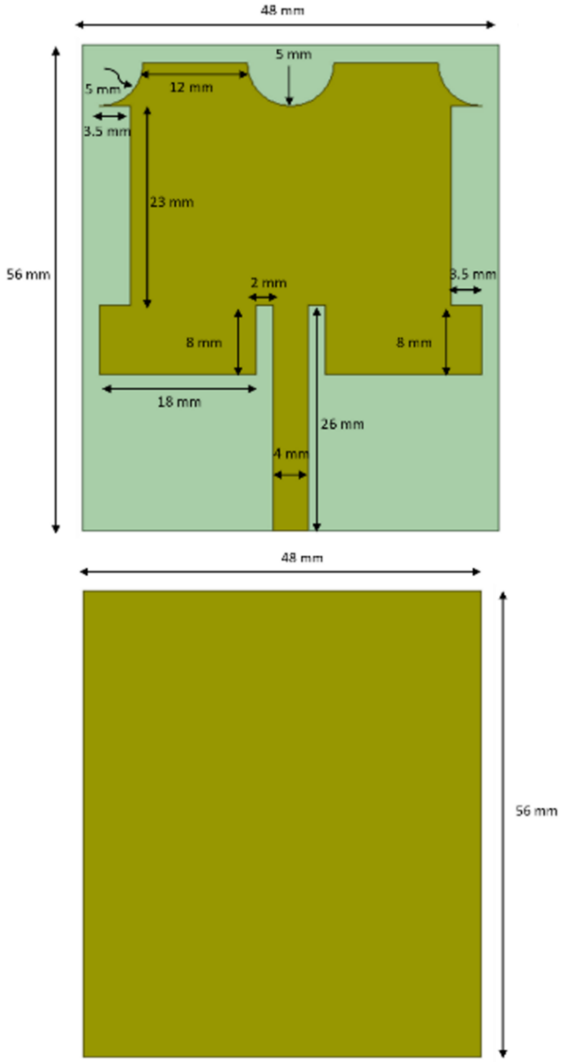

Figure 1: Structure of antenna, top and bottom views.

Engineered to function at 2.45 GHz within the ISM band, this antenna design is optimized for a wide range of biomedical applications. Its reliable performance makes it ideal for remote health monitoring, where continuous, non-invasive tracking of physiological parameters is crucial.

Additionally, it is highly effective for microwave-based imaging techniques, enabling high-resolution scans for medical diagnostics. The antenna's compact size, biocompatibility, and flexibility further enhance its applicability in wearable health devices, supporting the development of portable, user-friendly solutions for real-time health assessment and imaging.

The research gap identified is the need for reliable, efficient antennas that perform well in dynamic on-body environments without compromising size, comfort, or performance. The current work presents a design optimized for operation at 2.45 GHz within the ISM band, making it highly suitable for biomedical applications. It features a compact, biocompatible, and flexible structure, making it ideal for integration into wearable devices. This design supports remote health monitoring and microwave-based imaging, significantly enhancing real-time diagnostics and health assessments. The proposed antenna structure features a microstrip patch, selected for its stable radiation pattern and ease of fabrication. It is fed using an inset-fed line, which facilitates efficient power transfer to the patch. The feed line is precisely positioned to minimize signal reflections and achieve optimal impedance matching.

A PDMS substrate, with a relative permittivity of 2.6, is employed to support the patch. Choosing PDMS as the substrate material provides the required flexibility and biocompatibility, making it an ideal choice for wearable biomedical devices. The key design parameters of the proposed antenna are outlined as follows: The antenna is designed to operate at 2.45 GHz, a frequency widely used in wireless communication and medical applications. Polydimethylsiloxane (PDMS) is selected as the substrate material due to its flexibility and biocompatibility, making it ideal for wearable biomedical devices. The substrate has a thickness of 1 mm, offering a suitable compromise between mechanical flexibility and effective electrical performance. The patch dimensions are precisely optimized to ensure resonance at the target frequency of 2.45 GHz. A 50 Ω microstrip feed line is employed to facilitate optimal power transfer, thereby supporting efficient and reliable antenna operation. The design parameters of the proposed microstrip patch antenna are initially determined based on the standard analytical equations presented in Balanis' *Antenna Theory* to ensure operation within the 2.4–2.5 GHz ISM band.

The antenna was designed and simulated using HFSS, a leading electromagnetic simulation software. Key simulation parameters, including return loss, gain, bandwidth, and efficiency, were analysed to evaluate the antenna's performance. HFSS provides a detailed analysis of the antenna's behaviour, facilitating the optimization of the design to meet the desired specifications.

3 Results and Discussion

The simulation results for the proposed PDMS-based antenna demonstrate outstanding performance, as detailed in the following sections. The antenna was simulated to assess key performance metrics, including return loss, gain, bandwidth, and efficiency.

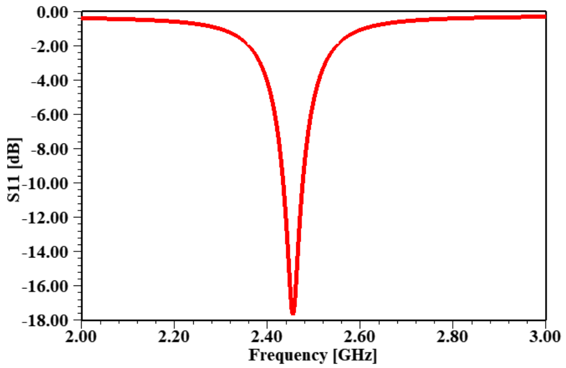

Figure 2: Return Loss (S_{11}) plot for proposed antenna.

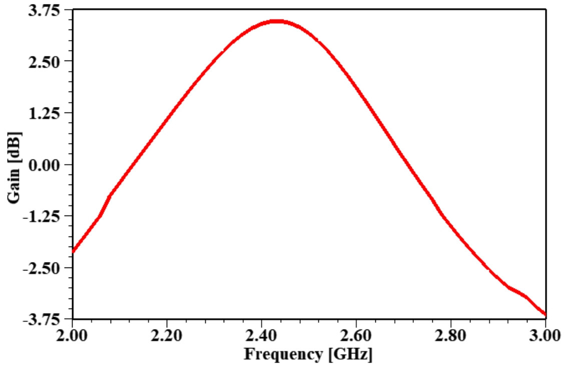

Figure 3: Gain plot for proposed antenna.

3.1 *Return loss*

Return loss is a key parameter that indicates how well an antenna is matched to its transmission line or feeding network. A high return loss (more negative in dB) implies low signal reflection, which means that most of the input power is radiated or absorbed by the antenna rather than being reflected back.

The primary reason for low signal reflection, or high return loss, in well-designed PDMS-based flexible antennas is the effective impedance matching between the antenna and the feed line, which is achieved through careful optimization of the Antenna's geometry and thoughtful selection of materials.

The material properties of PDMS, including its low dielectric constant and low loss tangent, support stable electromagnetic performance and help maintain good impedance matching across a broad frequency range. Additionally, the antenna geometry—such as slot configurations, patch dimensions, and ground plane modifications—is precisely tuned to align the input impedance with the standard 50-ohm system, thereby minimizing signal reflection. The conformal nature of PDMS further enhances performance by allowing the antenna to closely follow the contours of the human body, reducing air gaps and discontinuities that could otherwise lead to impedance mismatches.

As shown in Figure 2, the simulation results indicate a return loss of -18 dB at 2.45 GHz, demonstrating excellent impedance matching and confirming the antenna's superior performance.

3.2 *Gain*

Antenna gain quantifies its capacity to direct radiated energy towards a specific area. The proposed antenna demonstrates a gain of 3.6 dB at 2.45 GHz, making it ideal for biomedical applications such as wireless health monitoring and microwave imaging, as shown in Figure 3.

3.3 *VSWR*

Figure 4 displays the Voltage Standing Wave Ratio (VSWR) curve for the proposed antenna. The VSWR serves as a crucial measure of the performance of the antenna's impedance matching, with values close to 1:1 indicating optimal performance. As shown in the plot, the VSWR is well below 2 across the operating frequency of 2.45 GHz, demonstrating desirable performance and confirming efficient power transfer. This favourable VSWR indicates that the antenna is appropriately matched to the source, ensuring minimal signal reflection and enhancing its suitability for biomedical applications.

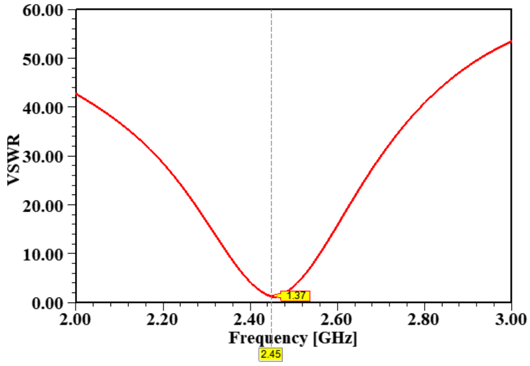

Figure 4: VSWR plot for proposed antenna.

3.4 *E field*

Figure 5 depicts the electric field (E-field) distribution of the proposed antenna at 2.45 GHz, showcasing a peak E-field strength of 23266.54 V/m. This high E-field strength signifies efficient energy radiation and optimal performance at the target frequency. The consistent and focused E-field distribution highlights the antenna's effective radiation pattern, essential for applications like wireless health monitoring and microwave imaging. The robust E-field at 2.45 GHz reinforces the antenna’s suitability for biomedical applications, ensuring dependable and efficient operation.

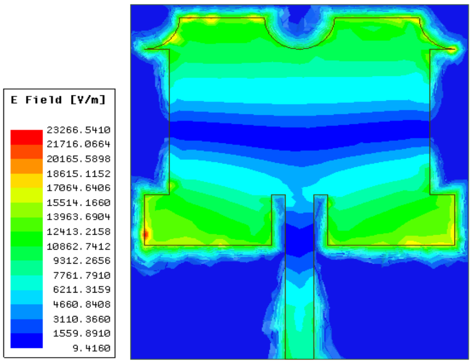

Figure 5: Electric field distribution for the proposed antenna.

3.5 *Efficiency*

Antenna efficiency quantifies its capacity to convert input power into radiated energy. Simulation results show that the proposed antenna delivers enhanced efficiency, a remarkable achievement for a flexible, wearable antenna design.

The proposed PDMS-based flexible antenna offers several distinct advantages over traditional rigid antennas. The flexibility of the PDMS substrate allows the antenna to adapt to the contours of the human body, making it ideal for integration into wearable biomedical devices. Furthermore, PDMS is a biocompatible material, ensuring the antenna’s suitability for long-term use in medical applications [10], [11]. Antenna efficiency quantifies its capacity to convert input power into radiated energy. Simulation results show that the proposed antenna delivers enhanced efficiency, a remarkable achievement for a flexible, wearable antenna design.

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The simulation results highlight the antenna's robust performance at the target frequency of 2.45 GHz, featuring a return loss of -18 dB, a gain of 3.6 dB, and an E-field strength of 23266.54 V/m. These characteristics make the antenna highly suitable for wireless health monitoring systems, microwave imaging, and other biomedical applications, as evidenced by similar antenna designs in the field. However, challenges remain in the practical implementation of flexible antennas. The mechanical deformation of the antenna due to bending or stretching could affect its performance [12], [13]. Future research will aim to enhance the antenna’s robustness and ensure consistent performance under dynamic conditions [14], [15].

Polydimethylsiloxane (PDMS) has become a preferred substrate for flexible antennas, especially in wearable and adaptable applications. Its unique properties, such as high flexibility, biocompatibility, chemical stability, and low dielectric constant, make it suitable for use in dynamic and challenging environments [16], [17]. A structured list of reference papers on PDMS-based flexible antennas, along with a brief comparison of their approaches, methodologies, and key findings is given in Table 1.

Table 1: Comparisons on PDMS-based flexible antennas.

Study	Focus Area	Operating Bands	Key Features	Applications	Ref.
Dual-Band PDMS Antenna	Dual-band wearable use	ISM Bands	High flexibility, bending resilience	Wearable Sensors	[10]
PDMS as Substrate	Material evaluation	Wideband	Low cost, robustness	Body-Centric Communication	[11]
HIS-Based PDMS Antenna	Radiation efficiency	ISM, WBAN	High impedance surface design	On-Body Networks	[12]
Evaluation of PDMS	Property analysis	Wideband	Stable under environmental changes	Flexible Antennas, Sensors	[13]
PDMS-Based Dual-Band Antenna	Dual-band WLAN/ISM	ISM, WLAN	Compact design, high efficiency	ISM and WLAN Devices	[14]
SU-8/PDMS Hybrid Antenna	Hybrid material approach	RF Bands	SU-8/PDMS combination for flexibility	RF and Wearable Devices	[15]
Liquid Metal-PDMS Antenna	Stretchability improvement	Dual-Band	Liquid metal + PDMS for resilience	IoT and Body-Worn Devices	[16]
MIMO Antenna Using PDMS	Compact multi-mode design	5G, IoT Bands	Beamforming, multi-element setup	IoT, 5G Wireless Communication	[17]

Table 2: Performance Comparison of PDMS-based Flexible Antennas with Respect to Return Loss, Gain, and VSWR.

Gain (dB)	VSWR	Operating Frequency (GHz)	Ref.
3.4	1.2	2.45	[18]
3.2	1.3	2.45	[19]
3.5	1.4	2.45	[20]
3.1	1.1	2.45	[21]
3.3	1.2	2.45	[22]
3.6	1	2.45	Proposed work

Table 2 provides an in-depth analysis of critical performance metrics for various PDMS-based flexible antennas, emphasizing key metrics such as return loss, VSWR, gain and electric field strength. These parameters play a pivotal role in assessing the antennas' overall efficiency, particularly in terms of impedance matching, radiation characteristics, and their suitability for biomedical applications. This comparison highlights the proposed antenna's superior return loss and electric field strength, confirming its suitability for use in wearable biomedical devices [23], [24]. Additionally, the VSWR values indicate efficient impedance matching across the designs, ensuring effective power transfer.

4 Conclusions

This study presents the successful development and evaluation of a compact, flexible antenna employing a PDMS substrate, specifically engineered for on-body biomedical applications within the 2.4–2.5 GHz ISM band. The antenna demonstrates excellent electrical performance, including wide impedance bandwidth, notable gain, and stable radiation characteristics, all while maintaining a low-profile, body-conformal structure. The biocompatible and flexible nature of PDMS not only ensures safe and comfortable integration with the human body but also supports consistent functionality during movement and prolonged use. Simulations and experimental assessments, including return loss, gain, and SAR analysis, validate the antenna's efficiency and compliance with international safety standards.

Moreover, this work addresses critical challenges in wearable antenna design, such as mechanical stability, miniaturization, and performance degradation due to body proximity. The incorporation of geometry optimization, material tuning, and multilayer tissue phantom modeling ensures robust performance in realistic biomedical environments. While the use of PDMS may involve higher manufacturing costs, its unique properties make it a suitable choice for specialized, high-precision healthcare applications such as wearable health monitoring, medical telemetry, and telemedicine systems.

Future work may focus on enhancing durability under dynamic body movements through stress-strain simulations, refining fabrication techniques, and scaling the design for broader biomedical use. Overall, the proposed antenna represents a promising solution for next-generation body-centric wireless communication systems, combining technical efficiency with user safety and comfort.

Author Contributions

D.S.: conceptualization, methodology, investigation, writing - reviewing and editing; S.K.: investigation, research design, data analysis, supervision; K.A.: conceptualization, data curation, project administration.

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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