

Partial Discharge Detection using UHF Sensor on High Voltage Equipment

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Abstract

High voltage transmission is essential for efficient energy transfer in power systems, relying on key components like transformers and Gas Insulated Switchgear (GIS). Detecting partial discharge (PD) is vital to prevent insulation failure and ensure system reliability. This study addresses the limitations of traditional PD detection methods, which are often intrusive and noisy, by employing Ultra-High Frequency (UHF) sensors for sensitive, non-invasive detection. The primary objectives were to use UHF sensors to study partial discharges in high-voltage equipment, identify insulation defects in laboratory settings, and analyze PD signals. HVAC tests were conducted to replicate PD events, with electromagnetic radiation measured using UHF antennas. The findings demonstrated that UHF sensors effectively capture PD-related electromagnetic signals, offering superior sensitivity and accuracy. This non-invasive method enhances the reliability and lifespan of high-voltage equipment by enabling early detection of insulation flaws, thereby improving maintenance and operational strategies for more consistent power delivery.

1. Introduction

High voltage transmission is essential for efficient energy transfer within power systems, heavily relying on critical components such as transformers and Gas Insulated Switchgear (GIS) [1]. Detecting partial discharge (PD) is vital for maintaining the reliability of high-voltage equipment, as undetected PD can lead to insulation failure and subsequent equipment breakdown [2]. Traditional PD detection methods include acoustic, electrical, and optical techniques, all of which have significant limitations such as susceptibility to ambient noise, invasiveness, and complexity of setup. The main challenge is the lack of efficient, reliable, and non-intrusive PD detection techniques. Ambient noise often affects acoustic methods, leading to false readings or missed PD events, thereby reducing diagnostic reliability [3-4]. Traditional PD detection methods include acoustic, electrical, and optical techniques, all of which have significant limitations, such as susceptibility to ambient noise, invasiveness, and complexity of setup [5].

To address these challenges, this study proposes using Ultra-High Frequency (UHF) sensors for non-invasive PD detection. UHF sensors provide the advantage of operating without disturbing the equipment and are highly sensitive to the electromagnetic signals emitted by PD occurrences. This approach promises significant improvements in the early detection of insulation faults, thereby enhancing the reliability and longevity of high-voltage equipment. The objectives of this study are threefold: to investigate the phenomenon of partial discharges in high-voltage equipment using UHF sensors, to measure PD within high-voltage

laboratory equipment to identify insulation defects and prevent pre-breakdown conditions, and to analyse the PD signals captured by UHF sensors.

2. Literature Review

Partial discharge (PD) is a localized electrical discharge that partially bridges the insulation between conductors. The main types include internal discharge, treeing discharge, surface discharge, and corona discharge. Internal discharges occur within the insulation material due to voids or cavities, posing significant risks as they can lead to catastrophic failures without warning [6]. TEV detectors are used to detect uneven electric field distributions early [6]. Treeing discharges create tree-like patterns in dielectric materials caused by contaminants, mechanical flaws, or prolonged high electric stress [6]. These "electrical trees" degrade insulation over time, increasing the risk of equipment failure. Surface discharges happen along insulation surfaces under high electric field stress, often at cable terminations or bushings due to insufficient grading. They can propagate over the surface, reducing dielectric strength. Corona discharges are visible discharges at sharp points on conductors exposed to high voltage in the air, creating a glow. Common in humid outdoor installations, they are typically harmless but require regular maintenance [7]. Effective PD management ensures the reliability of high-voltage equipment.

Partial discharge (PD) detection is crucial for ensuring the reliability of high-voltage equipment. Various methods exist, each with unique strengths and applications [8]. The electrical Detection method adheres to the IEC 60270 standard, focusing on measuring electrical signals emitted during PD events. It's widely accepted for its precision and ability to provide quantitative data on PD activity [9]. Chemical Detection is primarily used for power transformers; this method involves dissolved gas analysis (DGA). PD generates gases, such as hydrocarbons in oil-filled equipment, which are detected and analysed. Though effective for indicating the presence of faults, it offers limited information about the exact location and type of PD. Acoustic Detection is a non-intrusive technique that uses sensors like piezoelectric transducers or microphones to capture the sound waves produced by PD events [11]. Acoustic detection is widely used for monitoring transformers, generators, and high-voltage cables, allowing real-time detection and early maintenance interventions. The electromagnetic Wave Detection method captures the electromagnetic waves emitted during PD events [12]. It provides precise localization of PD sources, making it highly effective for monitoring gas-insulated switchgear (GIS) and power transformers. Despite its high sensitivity, it can be affected by signal attenuation and ambient noise interference [8]. Understanding and employing these detection methods help maintain high-voltage equipment's integrity, ensuring early detection and mitigation of potential failures.

3. Methodology

The flowchart of the project shown in Fig. 1 represents the workflow of this project. The flowchart also acts as a guide to help visualize the required step requirements to execute the project objective perfectly. The flowchart is divided into three stages, each representing the process required to successfully achieve the project's objective. Stage 1 involves studying partial discharge phenomena and UHF sensors and evaluating the UHF patch antenna method for PD measurement using UWB signals to gauge signal intensity. Stage 2 features an experiment in a high-voltage laboratory to measure partial discharge data with an HVAC circuit and UHF antenna sensor. The voltage will be increased to induce a PD signal, and if successful, data collection proceeds; otherwise, the experiment is repeated. Stage 3 focuses on transferring collected data to a digital storage oscilloscope for plotting and further analysis on personal computers.

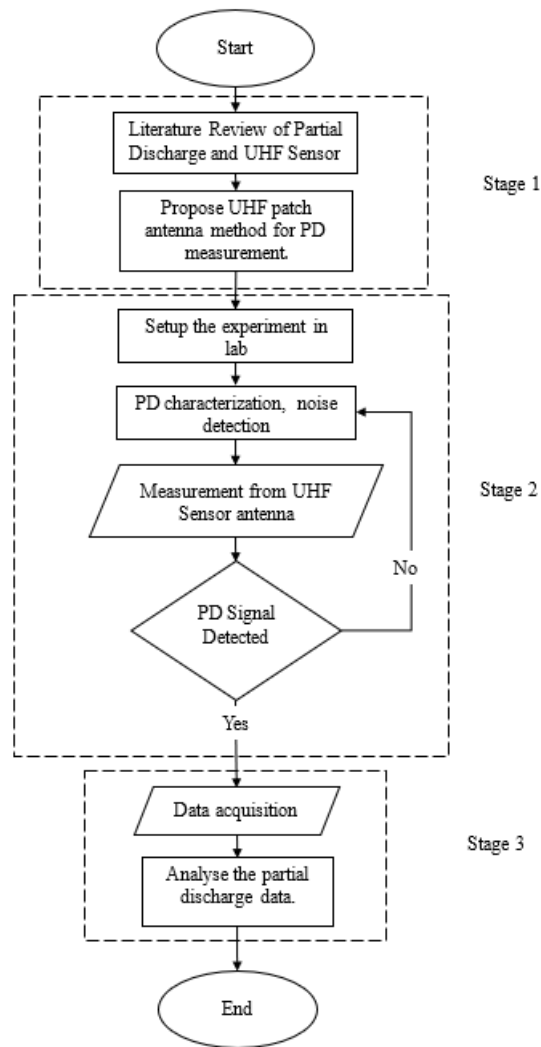


Fig. 1 Flowchart of the project for PD detection using the UHF sensor method

3.1 Method Used to Detect PD

The optimal method for detecting partial discharge in high-voltage equipment uses a UHF sensor with a patch antenna and ultra-wideband (UWB) technology. This method leverages the sensitivity of patch antennas to UWB pulses generated by partial discharges, allowing for accurate identification and analysis of PD events. Fig. 2 shows the UHF sensor antenna used in this research, including front and back views.

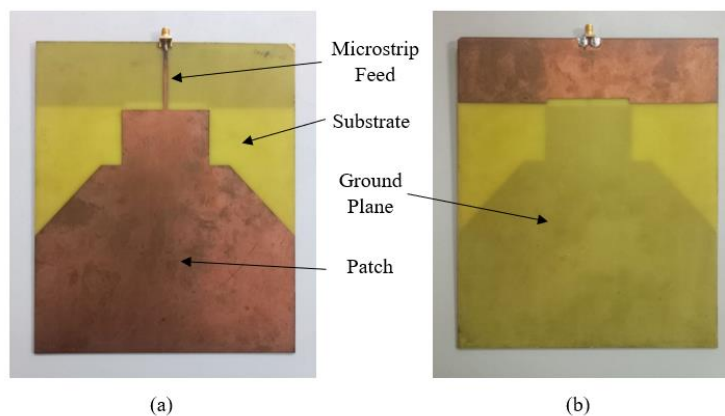


Fig. 2 UHF Antenna sensor used for partial discharge detection: (a) front view b) back view

Fig. 2 shows the front and back views of the UHF antenna sensor used for partial discharge detection in the high-voltage laboratory. The material used in the UHF sensor design in Fig. 2 is copper for the antenna and FR4 for the substrate. The bandwidth of the UHF sensor antenna used in the figure is 370-1300 MHz. This antenna is built on a 1.6mm thick FR4 PCB substrate with a relative permittivity of 4.4. The configuration of the ultra-wideband antenna model is shown in Figure 3, and the design parameters are listed in Table 1.

Table 1 Parameter of designed UHF antenna

Parameter	Value (mm)	Parameter	Value (mm)
Ls	240	Wf	3
Ws	210	Lf	52
Wp1	200	Lp2	43
Lp1	90	Wp2	33.5
Hs	1.6	Wp3	16
Lg	40	Wg	210

Fig. 3 illustrates the configuration of the antenna designed. The UHF antenna features omnidirectional radiation, allowing it to receive electromagnetic waves from all directions. This characteristic is particularly advantageous for use in GIS, where the precise location of the PD is unknown. The proposed antenna's frequency bandwidth is from 370 to 1300 MHz.

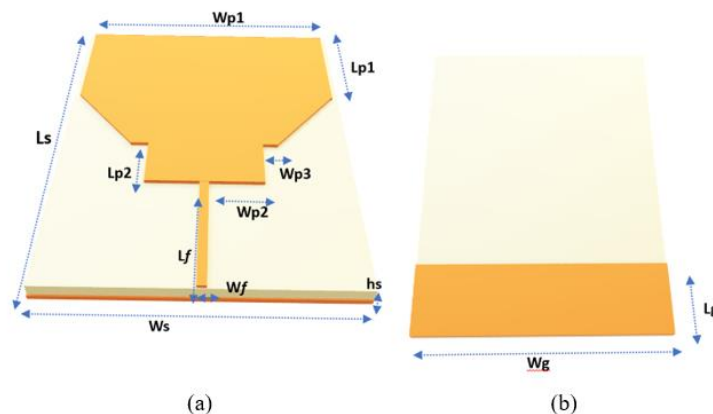


Fig. 3 Configuration of the UHF antenna model (a) front view (b) back view

3.2 Experimental Setup

The equipment is set up in the schematic circuit from Fig. 4 for the high-voltage laboratory experiment. The figure mentioned references the earlier article and a particular scientific journal, specifically addressing partial discharge measurement in a laboratory setting. The approach for detecting partial discharge pulses involves noise level identification, as the UHF antenna captures PD signals emitted as electromagnetic waves, prone to both external and internal noise interferences. The Faraday cage that encloses the experimental setup provides efficient shielding against outside electromagnetic noise. By frequently turning on and off the test transformer and capturing the noise pulses that emerge, internal noise in the lab setting is continuously monitored. The oscilloscope trigger is set to levels above this threshold after the noise level picked up by the UHF antenna is known, allowing the oscilloscope to catch PD pulses selectively. The partial discharge extinction voltage (PDEV) is the voltage at which repeating PD events stop.

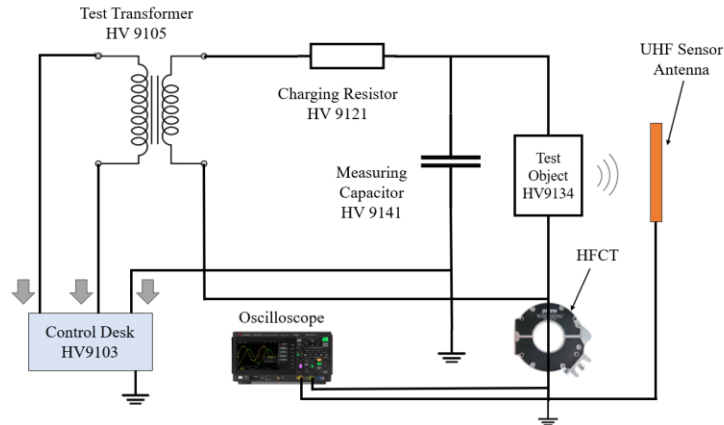


Fig.4 Partial discharge experimental setup

3.3 Analysis of Partial Discharge Characteristics

For high-frequency oil-immersed electrical equipment HFO(E) to remain reliable and long-lasting, partial discharge (PD) characteristics must be analysed. This essay explores the techniques used to identify partial discharge (PD) in the laboratory, with a particular focus on Ultra High Frequency (UHF) testing and a comparison of the results with High-Frequency Current Transformer (HFCT) testing. Additionally, it investigates the effects of applied voltage and the distance between detecting devices and PD sources on detection sensitivity. It also discusses the methods for identifying and removing noise to guarantee precise PD analysis.

4. Result

This section examines the characteristics of partial discharge in HFO(E) using both UHF and HFCT methods, comparing the detection sensitivity of the designed UHF antenna with HFCT. The noise level that occurs at the high-voltage lab will be analysed. The effect of the voltage and distance on the sensitivity will be examined to explore further and increase the understanding of the characteristics of the UHF sensor antenna.

4.1 Noise level of high-voltage laboratory

A thorough explanation of the UHF antenna's detection sensitivity for PD detection is given in this section. Many studies have investigated using UHF antennas to identify PD activity in various applications, including transmission cables, transformer oil, and air insulation. Because of this, the UHF antenna has been used in this investigation in conjunction with HFCT to detect partial discharges in the HFO(E) gas mixture. HFO(E) gas in a mixture with CO₂ is utilized due to its exceptional dielectric performance for gas-insulated switchgear applications [13]. Initially, UHF and HFCT are used to monitor the noise levels in the high-voltage laboratory. The HVAC partial discharge setup is built without voltage being applied to the test circuit. Researchers have described this technique for detecting noise levels in the currently available literature [14-15] The peak-to-peak voltage (V_{pk-pk}) of the no-load voltage noise pulses recorded by the HFCT signal is 9.8 mV, whereas the noise level detected by the UHF antenna is 10.5 mV (V_{pk-pk}). Similarly, the background noise levels recorded by the HFCT and UHF antenna after turning on the transformer are 10.1 mV and 11 mV (V_{pk-pk}), respectively. After 30 times measuring outside noise levels, it was discovered that the noise level in the HV lab constantly remained below 11 mV. Since the test equipment is protected from electromagnetic interference by a Faraday cage, the noise picked up by the UHF antenna indicates internal noise in the laboratory setting. Because of this, the trigger level for PD activities is set above 6 mV, knowing the noise value. This way, signals higher than this threshold, or 12 mV_{pk-pk}, are recognized as PD signals. Table 2 provides a summary of the noise level values.

Table 2 Background laboratory noise level detection

Sensor	No load voltage			Loaded Voltage		
	V _{max} (mV)	V _{min} (mV)	V _{pk-pk} (mV)	V _{max} (mV)	V _{min} (mV)	V _{pk-pk} (mV)
UHF	5.2	5.3	10.5	5.6	5.4	11
HFCT	2.5	7.3	9.8	2.8	7.3	10.1

4.2 Effect of distance on the sensitivity

The UHF antenna was positioned at various distances from the PD source at 50, 75, and 100 cm intervals to investigate the antenna's sensitivity for PD detection. The protrusion defect and the point of PD origin were represented by the point-plane electrodes. The HFCT was the sensor that confirmed that the intended antenna could detect PD when clamped to the ground wire. The 10% HFO(E) mixture with CO₂ was investigated at a voltage of 13 kV. The PD signals that were recorded are shown in Fig. 5. The UHF sensor was observed to be more sensitive to partial discharges than the HFCT sensor at 50 cm. The intended antenna, however, could still pick up the PD pulses at 100 cm. The outcomes of HFCT and UHF at various distances are summarised in Table 3. The developed antenna is determined to have PD signal detection capability comparable to HFCT sensitivity. A digital oscilloscope was linked to the antenna and HFCT sensors via a 50-Ohm coaxial wire.

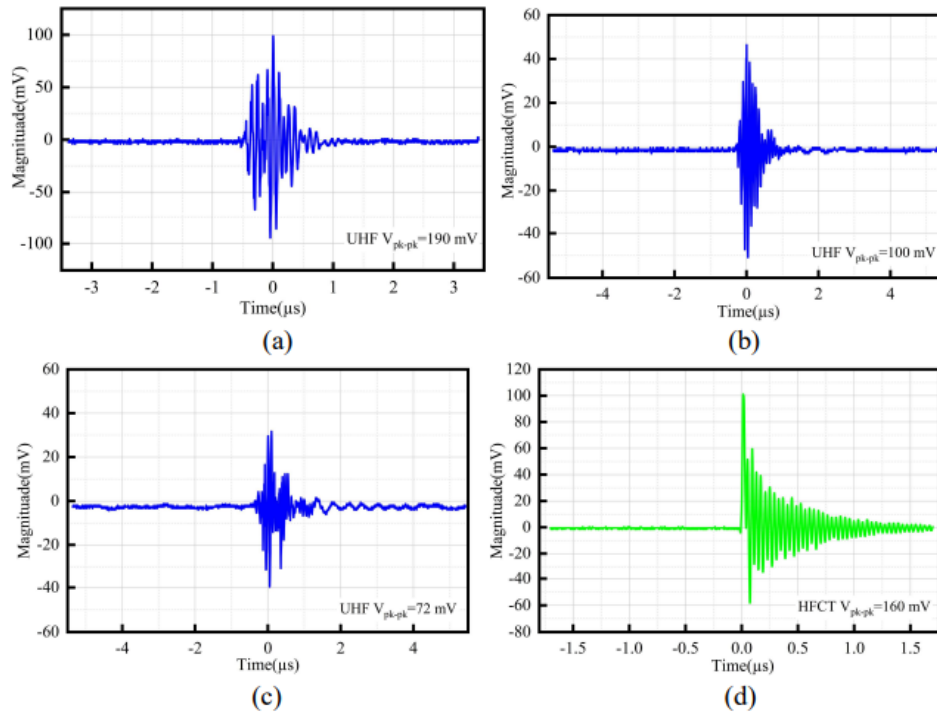


Fig. 5 Antenna placement at (a) 50 cm, (b) 75 cm, (c) 100cm, and (d) HFCT detected signal

The constructed antenna has detected a PD pulse signal at a distance of 50 cm, with an amplitude of 190 mV, as shown in Fig. 5. The signal-to-noise ratio (SNR) of the intended antenna is $(190 \text{ mV} / 11 \text{ mV} = 17.27)$ in linear SNR terms, and when translated to decibels (dB), the value is 24.75. This is because the background noise level detected by the same antenna was 11 mV. This estimate is consistent with the research findings [34]. This proves the antenna's excellent SNR and dependability in identifying extremely sensitive PD signals. An overview of the findings from UHF and HFCT at different distances is given in Table 3.

Table 3 UHF PD detected pulses at different positions from the PD source

Antenna position	V_{pk-pk} (mV)	V_{max} (mV)	V_{min} (mV)
50	190	100	92
75	100	48	52
100	72	32	40

4.3 Effect of voltage on the sensitivity

Fig. 6 shows the PD results of the HFO(E) and CO₂ mixture at 0.1 MPa pressure, recorded concurrently by the HFCT and UHF sensors. The observed PD pulse amplitudes are 64 mV, 112 mV, and 139 mV, respectively, when the applied voltage gradually increases from 17 to 19 kV. These voltage values are selected to evaluate the UHF

antenna's PD sensitivity in relation to the HFCT throughout a range of voltages, from breakdown voltage to inception voltage. As expected, the PD pulses' magnitude noticeably increases from 64 mV to 139 mV as the applied voltage increases. This investigation also confirmed the vulnerability of the projected antenna to partial discharges.

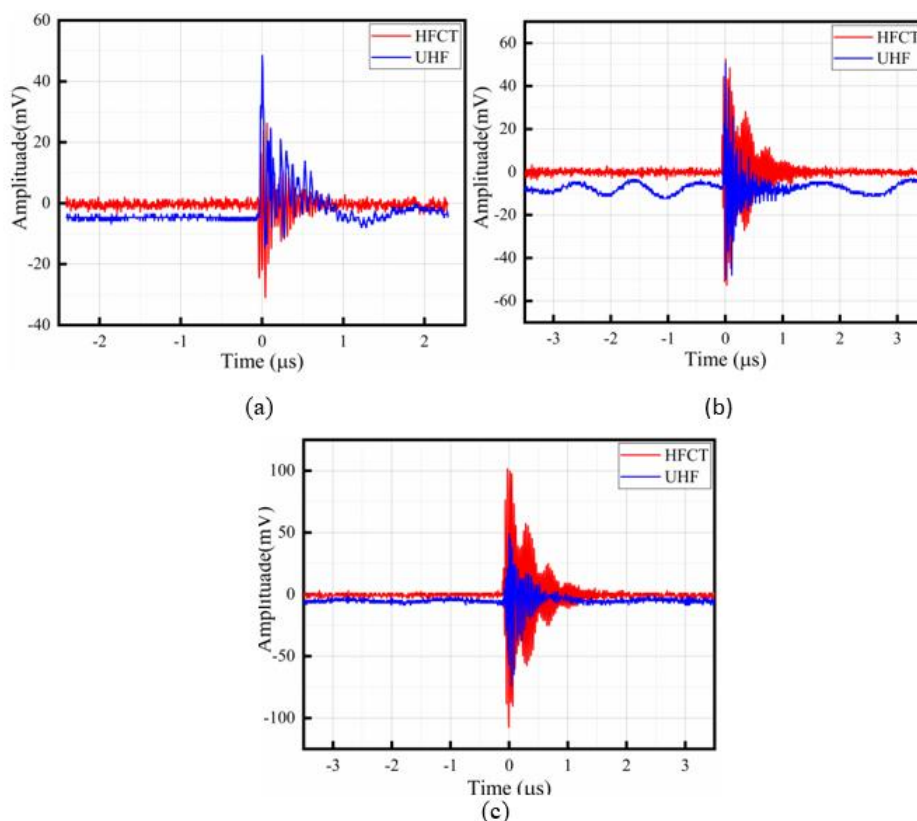


Fig. 6 Comparison of PD pulses magnitude simultaneously detected by UHF and HFCT at voltages (a) 17 kV, (b) 18 kV, and (c) 19 kV

4.4 Summary

The experimental study aimed to enhance the use of Ultra-High Frequency (UHF) sensors for detecting partial discharge (PD) in high-voltage equipment. Conducted in a controlled high-voltage lab, the research initially measured background noise to ensure accurate PD detection. It was found that the noise levels were within acceptable limits, enabling reliable PD measurements. The study then evaluated the UHF sensor's sensitivity at various distances from the PD source, revealing that the sensor maintained accurate detection even at longer ranges. The sensor's performance was also tested across different voltage levels, demonstrating increased PD pulse magnitude with higher voltages. The UHF sensor showed superior sensitivity and accuracy compared to the traditional High-Frequency Current Transformer (HFCT) method. The study confirmed that UHF sensors are highly effective for early and accurate PD detection, offering significant advantages for high-voltage equipment maintenance and operational efficiency.

5. Conclusion

The research on partial discharge (PD) detection using Ultra-High Frequency (UHF) sensors in high-voltage equipment has led to notable advancements, significantly improving the reliability and efficiency of power systems. The study aimed to explore PD phenomena, measure PD in high-voltage laboratory settings, and analyze PD signals through UHF sensors. The results demonstrated the capability of UHF sensors to capture electromagnetic signals associated with PD events effectively, showcasing high sensitivity and non-intrusiveness. This method offers precise detection of PD activity, thus enabling early identification of insulation faults, which is crucial for extending the lifespan and reliability of high-voltage equipment.

Future work should enhance UHF sensor technology to achieve even greater sensitivity and broaden its applicability to various high-voltage equipment types. Additionally, integrating advanced data analysis techniques and machine learning algorithms could significantly improve PD signal interpretation, leading to

more accurate diagnostics and predictive maintenance strategies. Such advancements would ensure more efficient power system operations by minimizing the risk of insulation failures and associated disruptions. Adopting UHF sensors for PD detection marks a substantial step forward in maintenance and operational strategies for high-voltage systems, promoting more dependable and consistent power delivery.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper

Author Contribution

The author attests to having sole responsibility for the following: planning and designing the study, data collection, analysis and interpretation of the outcomes, and paper writing.

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