473 kV lightning impulse test of an insulator embedded in pressurized and heated liquid nitrogen

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ABSTRACT

Liquid nitrogen is the most common fluid for cooling superconducting power engineering devices. The dielectric strength of an insulator rod embedded in liquid nitrogen at a pressure of 0.3 MPa was investigated with lightning impulse voltage series of 20 impulses of ±473 kV for gap lengths up to 50 mm between a grounded plane and a high voltage electrode in the shape of a bell. The influence of boiling due to quenching of the superconductor was simulated by heating impulses with a duration of 10.1 s. Before triggering the heater impulse, the liquid nitrogen was in the subcooled state i.e., a pure liquid. Transient bubble generation due to the heater impulse was confirmed by video recording through an observation window of the cryostat. The voltage of 473 kV was kept by a gap length of 18 mm in case of impulses of positive polarity. A gap of 30 mm was necessary in case of negative polarity. Hence, a strong polarity effect was found. Calculated field values based on the experimental results do not exceed limits used for the high voltage design study for a support insulator of a superconducting fault current limiter.

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1. INTRODUCTION

Increasing fault currents due to rising power demand or enhanced meshing is a critical issue for future grid planning [1]. One option for fixing the problems of increasing fault current is the use of superconducting fault current limiters (SFCL) [1]–[3]. SFCL for medium voltage level exist or have been operated in prototype projects in grid [4]–[6]. For higher voltages projects were reported e.g. in [7]–[9]. The presently most advanced daily grid operating SFCL is operated in the 220 kV grid of UNECO in Moscow, Russia [10]. A study [11] discussed the feasibility of a 380 kV SFCL for Germany but dielectric issues were calculated on rough extrapolations of dielectric strengths because of lack of experimental data concerning voltage level and size effects. Hence, the design of a cryogenic large scale high voltage test facility is under discussion with consideration of the requirements of the 380 kV SFCL. Some sparkover experiments at voltages of few 100 kV and with gap lengths of few 10ths of mm performed with the already existing facility "Fatelini2" may deliver useful input for the design outline of the future large scale high voltage test apparatus. The present paper describes such a "medium scale" high voltage experiment.

Pressurized subcooled liquid nitrogen was selected as electrical field stressed coolant [12], [13]. The transition from the superconducting to the normal conductive state ("quench") is for the most superconducting large-scale devices, like fusion magnets unwanted and preferably a never occurring fault case. In contrast, for the SFCL, it is the core feature. Hence, the potential impact on the nitrogen fluid by heat input is an important topic [14]–[17].

Full wave standard lightning impulse waveform was selected for the described tests. An overview of lightning impulse breakdown voltage experiments with liquid nitrogen and without insulator was published in [18] with tests of negative polarity up to 475 kV. However, experiments are not listed explicitly with positive polarity above 100 kV (sometimes polarity is not clear). Therefore, it is foreseen to perform impulse tests with both polarities. Flashovers for liquid to solid insulator boundaries may occur in case a mechanical support structure is needed. Such a support structure is included as post insulator for the 380 kV SFCL design and was identified as one of the most critical locations for receiving compact dimensions of the cryostat [11].

The present paper describes the investigation on dielectric strength of an insulator embedded in pressurized subcooled liquid nitrogen with a heatable ground electrode. The target waveform was a standard lightning impulse of 480 kV.

2. SETUP AND TEST METHOD

The insulator was a round rod made of PE-HD because this material had shown a better resistance against flashover destruction compared to harder material at least for lengths up to 10 mm [19]. The insulator was fixed by a screw (material: PA 6.6 with glass fiber) on the bottom ground plane, which was made from stainless steel. The stainless steel high voltage electrode was arranged above the ground electrode and had the shape of a bell which can surround the insulator completely for adjustment of the zero distance. The room temperature dimensions are shown in Figure 1 for a gap example length between electrodes of 30 mm.

Electric field calculation is based on the assumption that the bell touched the insulator resulting in a triple point formation. A model for calculation of the electric field strength was established with the simplification that no gap exists between insulator and bell, i.e., there is not only a triple point but a triple ring. This simplification allows the use of a 2D model (Figure 2). It should be noted that the thermal contraction of insulators is higher than for metals. Hence, the insulator diameter was reduced in the model by 2% [20] due to the cooldown. The radius of the bottom torus part of the steel bell was kept at room temperature conditions of 15 mm because of the shrinkage of only 0.3% [20]. Finally, the outermost diameter of the cryogenic bell model is 1.31 mm smaller than the room temperature outermost diameter of the bell with 101 mm in case of a manufacturing tolerance of 0.

Electrodes and insulator were installed in the bath cryostat. The bell was fixed on a tube which can be moved in vertical direction by turning a hand wheel. Each turn of the hand wheel shifted the bell for 2 mm. The distance between the lowest point of the bell (C in Figure 2) and the plane at the point D is designated as “gap length”. It should be noted that the length between the triple point (A in Figure 2) where the rounded metal surface of the bell touched the insulator and the ground electrode triple point (B) was 15 mm longer than the gap length. Heating of the ground plane was verified by bubble observation through one of the windows of the cryostat by using a webcam. Video recording was adjusted to a resolution of 320 * 240 and a rate of 15 frames per second. The hand wheel for distance variation between the electrodes was fixed in air on top of a cryogenic bushing. This bushing is made of resin impregnated paper (manufacturer: HSP, Germany). The bushing has an operation voltage for standard lightning impulses of 550 kV and was fixed on the cryostat lid equipped with sensors for temperature and liquid nitrogen level (Figure 3).

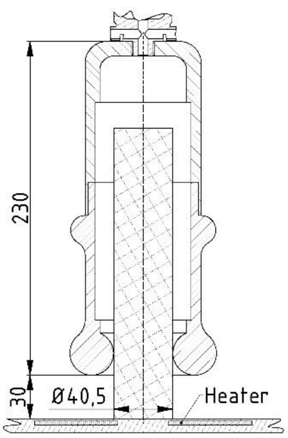

Figure 1. Insulator between high voltage “bell” electrode and heatable ground plane

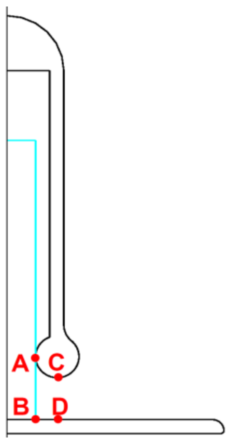

Figure 2. 2D BEM model of bell to plane setup with insulator

The lighting impulse was generated by a Marx generator mainly based on elements from a commercial construction kit (MWB, today: Pfiffner group) which is designed for a maximum stage number of three (Figure 4). Enhancements were done to extend the setup to a 4-stage device with the target to achieve standard lightning impulse waveform with peak voltages up to 480 kV for the load Fatelini2 including the high voltage divider. The 480 kV limit was set by the high voltage divider Hilo-Test HVT 300 RCR.

The cryostat was filled with liquid nitrogen. Then the pressure was increased to 0.3 MPa (absolute). After waiting for about 1 h the fine adjustment of the selected gap length was done and the temperature of liquid nitrogen was measured. Then the temperature measurement was removed and the high voltage tests were started. Firstly, a function check of the Marx generator was done with a voltage below 100 kV. Next, impulses with 200 kV, 300 kV, and 400 kV were applied. These 4 impulses were single impulses if no voltage breakdown happened. Finally, 20 lightning impulses were done with a peak voltage of 473 kV because the available construction kit elements did not allow to reach the target value of 480 kV. The minimum waiting interval between high voltage impulses was set to 3 min in case of no breakdown. In case of a voltage breakdown the minimum waiting duration was increased to 5 min.

Synchronizing of webcam, heater and spark gaps was initiated by webcam recording. The heater was manually started 2 seconds after begin of video recording and operated for 10.1 s. The spark gaps were triggered automatically 10.0 s after start of heating in order to ensure high voltage impulse application during the heating duration. Heater power supply voltage, current and power were recorded with an USB oscilloscope to verify heating duration and average heater power of 550 W.

Starting time of nitrogen gas bubble ascension in relation to the video recording was visually identified. Video recording was stopped about 20 s after lightning impulse triggering. Temperature measurement was reconnected after the 20 impulses with 473 kV for control if the liquid nitrogen is still subcooled. The gap distance for the next test day was already adjusted to the value of the next planned distance value in order to minimize length changes during the next high voltage test series. However, it was still necessary to fine tune the distance before the high voltage series on another day. Finally, the pressure was released to allow temperature recovery as well as liquid nitrogen filling before the next tests.

The number of breakdowns is not limited for high voltage tests with self-healing liquid nitrogen as long as no relevant degradation of the electrode surface occurs. However, fast degradation of the insulator surface had been taken into account for flashovers along the insulator to liquid nitrogen boundary. In addition, it cannot be excluded that insulator surface damage may also happen due to near breakdown through liquid nitrogen without direct touching the insulator by the breakdown channel. Therefore, the test procedure was organized in a way to obtain a low number of voltage breakdowns. Hence, the high voltage tests started with a large gap of 50 mm where a low breakdown probability was expected. Then the distance was reduced for 10 mm if no voltage breakdown happened. Both polarities were examined in order to investigate a polarity effect.

In case breakdowns happened, it was the aim to find a combination of gap lengths at which no breakdown happened for all 20 impulses at 473 kV and a gap length 2 mm lower, where breakdowns occurred. The shortest gap length at which no voltage breakdown happened was than assigned as “withstand gap length” for the test voltage of 473 kV under the conditions mentioned before. Consequently, the considered “breakdown gap length” for 473 kV was 2 mm shorter.

Figure 3. Assembly of insert with bell to plane setup in the cryostat

Figure 4. Cryostat with bushing, divider (orange color, right from cryostat, partly hidden by the cryostat), and Marx generator

The rise time of the high voltage divider is specified by the supplier as 60 ns. In most cases an oscilloscope Tektronix TDS 3012C was connected on the measurement cable termination. The usage of USB oscilloscope TiePie HS5-530XMS allowed recording of more samples but it was slower to handle. The impulse parameter analysis was done manually according to the withdrawn standard IEC 60060-1: 1989 [21]. The usage of this standard was considered as tolerable because the impulse waveforms did not show overshoot.

3. RESULTS

The high voltage impulse did not reach the target peak value of 480 kV but only 473 kV ±3 kV. The front time was around the upper limit of the tolerance for standard lighting impulses and exceeded the limit of 1.56 µs in about 10% of the impulses. Hence some tests were no standard lightning impulses but only lightning impulses. The time to half value was 50 µs ±2 µs, which satisfies the criterion for standard lightning impulse.

A maximum temperature of 78.7 K was measured for liquid nitrogen near the cryostat inner wall at the height of the ground plate after reconnection of the Pt100 sensors after the high voltage tests. This temperature value is well below the saturation temperature of 88 K for a pressure of 0.3 MPa [22]. Hence it can be concluded that the not heated liquid nitrogen was subcooled during all high voltage tests.

For the 50 Hz heater voltage waveform it takes about 5 cycles after switch on until the final sinus shape was reached. Manual switch on of the heater caused sometimes a delay up to 1 s with respect to the video recording time. Transient boiling due to heater operation was confirmed by video recording for all impulse tests. Heater power of 550 W ±10 W was verified. Nucleate boiling did not occur immediately with starting the heater. Instead, nucleate boiling retardation occurred with the largest amount of bubbles usually bridging nitrogen fluid space between plate and bell. This happened randomly about 1 s up to 2 s before the high voltage impulse. Then boiling continued with lower bubble intensity and disappeared gradually several seconds after stopping the heater.

The high voltage tests for the setup and under the conditions mentioned above delivered a breakdown voltage of +473 kV for the breakdown gap length between the electrodes of 16 mm. The withstand gap length for the voltage of +473 kV was 18 mm. In case of negative polarity, the withstand gap length for the voltage of -473 kV was 30 mm. For the gap length of 28 mm a disruptive discharge happened already at -400 kV and damaged the insulator. A further impulse test at -400 kV with the same distance of 28 mm caused a destruction of the insulator. No further high voltage was applied to the damaged setup. Test sequence can be seen in Figure 5, where black icons were used in case of 20 impulses of ±473 kV with no breakdown. Red symbols are used in case of breakdown. 1/20 above an icon means that for this series exactly 1 voltage breakdown was measured during 20 impulses with ±473 kV. (x) means that this single voltage breakdown occurred for impulse number x out of the 20 impulses. 2/0 means that 2 breakdowns happened before reaching -473 kV.

White and blue light emissions from insulator surface were identified for few seconds after disruptive discharges only. A unique observation was the missing light of the 50 W LED spot in Figure 6. This spot had usually illuminated the interior of the cryostat. Because this spot failed due to a disruptive discharge, the video frame is darker than with LED illumination. The light shown in Figure 6 was mainly generated from the insulator after the disruptive discharge (besides minor background light from outside the cabin). The red point below the plate was the indicator of heater operation. This means that breakdown happened before stop of heating. One can recognize some boiling activity especially on the right of the insulator directly above the ground plate as well as boiling on the left side between plate and rounded torus shaped end of the bell.

The electrical field strength calculation was done with the boundary element method program csp [23]. A 2D model was established for the negative withstand gap length of 30 mm. Figure 7 shows the electric field strength values along the boundary between PE insulator rod and liquid nitrogen (B to A) and the field within liquid nitrogen vs. the vertical distance from the grounded plate (D to C). The maximum electric field was not expected to exist at the lowermost point of the high voltage torus (C) because of the large diameter of the grounded plate and the cryostat wall. Therefore, a calculation of the field along the bottom half of the bell torus was added. Figure 8 shows the electric field along this half circle (A – C – F).

An electric field strength of 7.5 kV/mm was calculated for the liquid nitrogen near the high voltage triple point (A) whereas the field strength within the liquid nitrogen near the ground triple point (B) was calculated as 13 kV/mm. This value is also calculated near the ground plate location below the lowest point of the torus (D). The field strength near the lowest point of the torus (position C, angle 270°) was calculated as 25 kV/mm. The highest field value of 26 kV/mm was found on the torus for an angle of 298°.

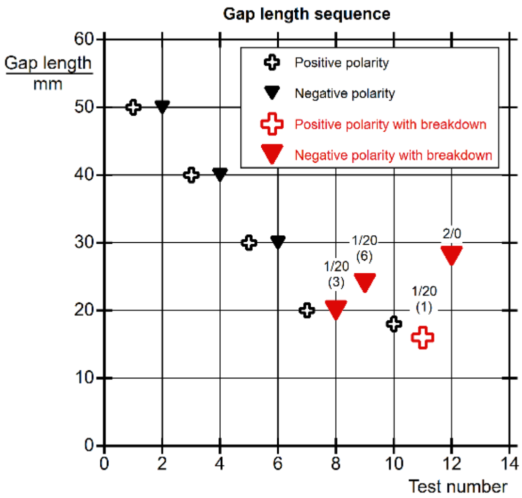

Figure 5. Gap length vs. test sequence number for the performed high voltage tests

Figure 6. View through the circular cryostat observation window without external LED illumination: The insulator emitted white and blue light after disruptive discharge with -474.5 kV

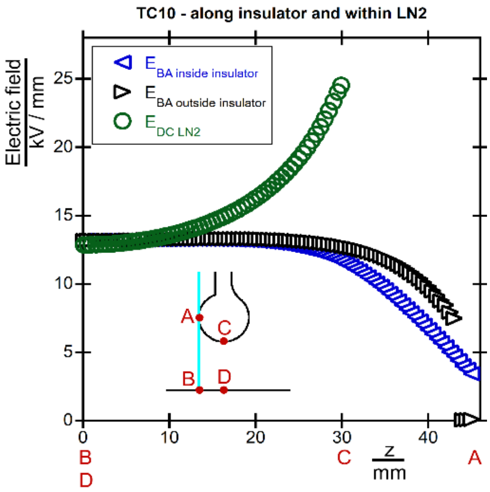

Figure 7. Electric field vs. distance z from plate along the insulator surface (BA) and within liquid nitrogen (DC)

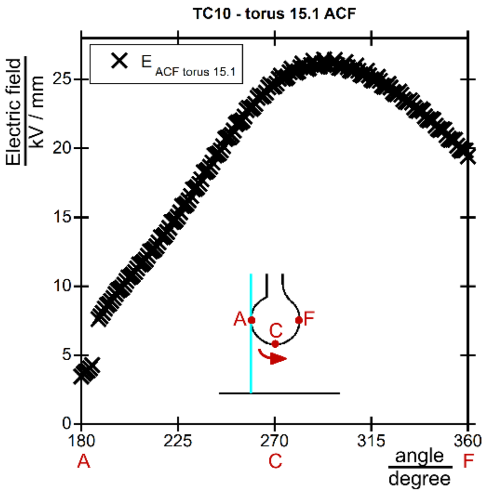

Figure 8. Electric field vs. angle along the lower half of the torus of the bell starting with 180° from the triple point A

4. DISCUSSION

The enhancement to a 4-stage Marx generator allowed 30% increase of the test voltage compared to the maximum output specification of 365 kV for the MWB construction kit [24]. The target value of 480 kV failed by 1.5%. Although this complies for the 3% tolerance for the test voltage peak value this is not an acceptable engineering way one should reason. Suitable lower damping resistors would increase the peak voltage and decrease the front time. However, the other configurations with the components available in the lab would have caused larger deviations from the front time value of 1.2 µs or hazardous transient voltage distribution within the Marx generator.

According to the results of the field calculation, the maximum field occurred on the torus far away from the triple points. However, the triple points can still be considered as weak locations especially in case of the ground side triple point where no relief existed and bubble density generated by heater was high. Consequently, sparkover within liquid nitrogen as well as flashover along the solid insulator are discussed.

Highest values concerning gap length and breakdown voltage listed within the literature review for lightning impulse breakdown in liquid nitrogen [18] was achieved in [25]. In [25], the largest gap length is 15 mm for a sphere to plane setup at 0.1 MPa (absolute). The average breakdown voltage is given as about 475 kV. Only values for negative polarity were reported. Two individual examples were described in detail with the lowest value of the maximum electric field calculated as 35 kV/mm, which is higher than the result calculated for Fatelini2, although the pressure was lower for the experiment reported in [25]. However, in [25], no heater was used. Average breakdown voltages between 255 kV and 425 kV were measured with up to 50% higher breakdown voltages for positive polarity compared to negative polarity in [26] for lightning impulse tests with stainless steel sphere to sphere and sphere to plane setups up to 8 mm distance.

Pressure increase in sphere to plane setup causes in uniform or weakly non-uniform fields usually an increase of breakdown voltage for liquid nitrogen at least up to 0.5 MPa [12], [13], [27], e.g., in [12] a breakdown voltage increase of about 20% was measured for a pressure increase from 0.1 MPa to 0.3 MPa. Due to the destruction of the sample of Fatelini2, it was not possible to add a test series at 0.1 MPa for comparison. Increase of pressure or decrease of temperature can lead to a reduction of the breakdown voltage for some configurations with strongly non-uniform fields [16], [17]. Such a behavior can be considered as unexpected but is well known for increasing pressure and strongly non-uniform air gaps [28]. The field distribution on the bell to plane setup of Fatelini2 is only weakly non uniform for the examined gap lengths. Consequently, such a behavior is not expected. In case of lightning impulse breakdown experiments with heater and uniform or weakly non-uniform field ([13], [14], [27]) polarity effect was low or was reduced after pressure increase.

Scaling effects are well known for AC breakdown behavior of liquid nitrogen. This means that not only the maximum field strength value must be considered but also e.g. the amount of "high field" volume. The percental factor for the definition what the expression "high" means is depending among others from pressure and temperature [29] which makes a comparison more complicated. For impulse voltage such effects also exist [17]. Therefore, already for experiments with liquid nitrogen without insulator "many parameters such as gap distance, voltage polarity, temperature, pressure, and synchronization contribute to a hardly predictable evolution of breakdown voltage" [17]. In case of flashovers along insulator surface it can be expected that the voltage breakdown values are lower or in the best case as high as without insulator.

Concerning flashovers, lightning tests with liquid nitrogen are reported in [26], [30] for flat samples with fiber reinforced plastic insulator and grounded plane to high voltage circle etched copper electrode setup. In this case 5% Weibull probability was reported to be below 250 kV for both polarities for a distance up to 120 mm. Lower flashover voltages were measured for positive polarity. The low dielectric strength can be explained mainly by the sharp edges of the etched electrodes.

Flashover setup with triangle to plane electrodes within liquid nitrogen on PTFE or PA surface is reported in [31]. Dielectric strength for positive polarity was higher than for negative polarity for standard lightning impulse tests in the open cryostat for gaps longer than 10 mm. The breakdown strength for positive polarity and 20 mm gap was higher than for 30 mm and negative polarity.

Lightning impulse tests for PMMA cylinders (height: 5 mm, diameter: 40 mm) within liquid nitrogen and between plate electrodes in an open cryostat were reported in [32]. Flashover voltage was 100 kV for both polarities, i.e. no polarity effect was found. Lightning impulse tests for PE cylinders (diameter: 40 mm, maximum height 6 mm or 10 mm) within liquid nitrogen and between plate electrodes in an open cryostat were reported in [19]. Two similar setups but with different edge rounding of the smaller top plate and different ground plane material (zinced iron and stainless steel) resulted in different results concerning polarity effects. In addition, a polarity effect without heater disappeared in case of heating.

Summarizing the experimental results, it can be concluded that polarity effects are different for different setups and one change e.g. by heating or minor shape modification can cause a different behavior. This can be an important information for design of a high voltage long gap test device in case of not only testing dielectric strength of liquid nitrogen but also in case of testing solid insulator flashover setups.

The destruction of the insulator supports the assumption that flashovers happened although it cannot be excluded that the destruction is caused by near breakdown in liquid nitrogen or that the disruptive discharges were in some cases sparkovers in the liquid nitrogen space and in other cases flashovers along the insulator surface.

Ribs can increase lighting impulse flashover voltage. Different PTFE insulators with a height of 15 mm were embedded in liquid nitrogen and subjected to AC high voltage [33]. The best rib shaped insulator achieves a flashover voltage increase of 13% compared to the flat insulator. However, the rib influence could not be tested in Fatelini2 because it is not compatible with the gap length variation mechanism. Furthermore, due to destruction of the insulator it was not possible to add AC tests. The field values for liquid nitrogen along the insulator did not exceed 3.4 kV/mm in the study [11], which is lower than the values at relevant locations for Fatelini2 with at least 7.5 kV/mm (Figure 7, E_{BA} outside insulator near A). However, lightning impulse triggering was heater duration determined and did never meet the random bubble occurrence maximum which may result in a lower breakdown voltage.

5. CONCLUSION

220 lightning impulses of ±473 kV were applied on the bell to plane setup with the upgraded Marx-generator before damaging the PE insulator. Withstand gap length was 67% larger for negative polarity. The damage of the insulator by voltage breakdown number 4 confirms the test method of starting with large gaps and a low probability of voltage breakdown in order to achieve a reasonable number of tests. Up and down methods which cause a large number of breakdowns would lead to an unacceptable experiment duration due to sample replacement or to low test numbers.

Prior experiments and tests of other researchers had shown that the breakdown voltage can be strongly affected by changes of one from multiple parameters like gap length, pressure, high field volume, and heating already in case of a sparkover within liquid nitrogen without insulator. The presence of the solid insulator together with a missing field strength relief on the ground plate side increased the complexity of the situation. A field strength of 7.5 kV/mm was calculated for liquid nitrogen near the high voltage triple point for the withstand gap length of 30 mm in case of negative bell polarity and bubble generation.

The results support assumptions of a calculation for the 380 kV SFCL and causes no high voltage design revision for its support insulator section. Published experimental data above 473 kV for the performed lightning impulse tests for both polarities with insulator within pressurized subcooled liquid nitrogen does still hardly exist. Hence, the results can be tentatively used as input for the design of a test setup for higher sparkover and flashover voltages. An advantage of the detected strong polarity effect which is reversed to the one in air is the possible use of components with reduced air length and apply lightning impulses only with negative polarity in case of lab limitations. It must be checked by further experiments if the 380 kV SFCL design comprises reasonable safety factors. The bell to heatable plane electrode system with a new PE insulator is foreseen for AC withstand testing with Fatelini2 as the next cryogenic experiment.

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AUTHOR CONTRIBUTIONS STATEMENT

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Volker Zwecker	✓	✓	✓	✓		✓	✓	✓		✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, [SF], on request.

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