Inversion of distance and magnetic permeability based on material-independent and lift-off insensitive algorithms using eddy current sensor

Mingyang Lu*, Xiaobai Meng, Ruochen Huang*, Liming Chen, Anthony Peyton, Wuliang Yin*

Abstract — Eddy current sensors can be used to test the characteristics and measure the parameters of the conductive samples. As the main obstacle of the multi-frequency eddy current sensor, the lift-off distance affects the effectiveness and accuracy of the measurement. In this paper, a material-independent algorithm has been proposed for the restoration of the lift-off distance when using the multi-frequency eddy current sensor, which is based on the approximation under the thin-skin effect. Experiment testing on the performance of the proposed method is presented. Results show that from the dual-frequency inductance, the lift-off distance could be restored with a maximum error of 0.24 mm for the distance up to 12 mm. Besides, the derived lift-off distance is used for the inversion of the magnetic permeability. Based on a lift-off insensitive inductance (LII) feature, the magnetic permeability of steels can be inversed in an iterative manner, with an error of less than 0.6% for the lift-off distance up to 12 mm.

Index Terms — Eddy current; lift-off; material-independent; permeability measurement; non-destructive testing.

I. INTRODUCTION

Eddy current techniques are widely used in interrogating the conductive materials in diverse industrial non-destructive testing (NDT) [1-9]. Owing to its merits (including high adaptability and sensitivity), the eddy current sensor has been used for the testing of the material characteristics, detection of structural integrity, the inspection of surface crack fatigue, and measurement of material properties including thickness and electromagnetic (EM) properties (electrical conductivity and magnetic permeability). The EM properties of materials are directly linked to the phase fractions of alloys [4]. To increase material homogeneity, and thus improve consistency in the mechanical properties, significant advances in materials characterisation would be obtained if the EM property information could be determined online during steel production in a non-destructive and remote manner [4]. However, like other eddy current techniques (including the single-frequency eddy current testing and pulsed eddy current testing), the multi-frequency eddy current (MEC) testing is sensitive to the lift-off distance between the sensor and test piece (particularly for the surface-defected sample), which could influence the accuracy of the measurement [10-15].

To address the lift-off issue, strategies including optimization of the coil structure, signal processing techniques, and novel measurement methods have been proposed. By analysing the signature of receiving coils, Giguere et al. have found a lift-off point of intersection (LOI) feature using the PEC method [16]. The exploited LOI feature does not vary significantly with variation in coupling or increase in probe lift-off. Researchers have further optimized, polished, and implemented the LOI feature for the measurement of materials using PEC techniques [17]. Abu-Nabah has proposed a semi-quadratic system to reduce the lift-off effect in high-frequency apparent eddy current conductivity spectroscopy [18]. Moreover, a phase signature has been used by Yin et al. and Pinotti et al. from the multi-frequency inductance [19-21]. With the proposed phase signature, the inductance change caused by the test sample is less affected by the lift-off distance. However, it has been found the inductance phase is still sensitive to the lift-off around the inflection point (near to the peak frequency feature) [22]. Therefore, an algorithm has been proposed for compensating the lift-off noise of the impedance/inductance phase [22]. However, compared to the impedance or inductance, its phase is less sensitive to the test piece. Therefore, it is necessary to explore an alternative feature from the swept inductance instead of its phase.

Previously, to reduce the lift-off effect, approaches involve planar sensor designs, multi-frequency features (including zero-crossing feature, and peak frequency features), the lift-off invariant phenomenon (conductivity and permeability invariant phenomena), and the phase signature [22-30]. In this paper, an alternative method based on the material-independent phase term under the eddy-current thin-skin effect has been proposed, which has improved and extended the previous measurement range of the lift-off distance (from 6 mm to 12 mm) without sacrificing the accuracy. Experiment testing on different magnetic steels has been carried out. The lift-off distance can be restored from the inductance of dual high frequencies, which is shown independent of different materials. Moreover, an identical lift-off insensitive inductance (LII) feature has been found on the swept frequency inductance of different magnetic

This work was supported by [UK Engineering and Physical Sciences Research Council (EPSRC)] [grant number: EP/P027237/1] [title: Real-time In-line Microstructural Engineering (RIME)].

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steels. That is, multi-frequency inductance curves of different lift-offs nearly intersect on one point. By referring to the restored lift-off and the corresponding frequency of LII, the relative magnetic permeability of ferromagnetic steels has been retrieved.

II. MATERIAL-INDEPENDENT ALGORITHM AND LIFT-OFF INSENSITIVE INDUCTANCE FEATURE

A. Original analytical formulation

As shown in Fig. 1, the eddy current sensor is composed of three co-axial coil windings. Since the magnetic flux generated from the transmitter diverges for a considerable distance (the gap, $g$ between the transmitter and receiver, as shown in Fig. 1 and Table 1), particularly for a relatively large lift-off distance between the sensor and sample, the radius of the receiver and reference coil is designed larger than that of the transmitter to fully catch the reflected magnetic flux.

In recent years, the Dodd-Deeds formula [31] has been widely used for the inductance analysis of the air-core coil above the conductive plates [32-37]. For the designed eddy current sensor shown in Fig. 1, the inductance change caused by the test magnetic steel is given by the expression.

$$L_1 = K\int_0^{\infty} M_1 e^{-2aL_1}d\alpha$$

$$L_2 = K\int_0^{\infty} M_2 e^{-2aL_2}d\alpha$$

where $L_1$ and $L_2$ are the inductance change from the transmitter-receiver and transmitter-reference sensing pairs. $K$ is a constant related to the cross-section of the coil.

$$K = \frac{\pi \mu_0 N^2 (r_2 + r_1)}{2h^2(r_2 - r_1)(r_{12} - r_{11})}$$

In (3), $\mu_0$ is the magnetic permeability of the free space (or vacuum magnetic permeability). Three coils have identical coil heights, $h$, winding turns, $N$, and separation distance, $g$. The inner and outer radius of the transmitter coil is $r_{11}$ and $r_{12}$. The receiver and reference coil have the same inner and outer radius $r_{1}$ and $r_{2}$. The integrand consists of the coil-dependent magnitude part ($M_1$ and $M_2$) with the lift-off decay term ($e^{-2aL_1}$), and the material-dependent phase term ($\Phi$).

$$M_1 = \frac{P_1}{\alpha^2} e^{-\alpha(h+g)/(e^{-ah} - 1)}$$

$$M_2 = \frac{P_2}{\alpha^2} e^{-2\alpha(h+g)/(e^{-ah} - 1)}$$

where $P_1$ and $P_2$ are the integral of the Bessel series; $\alpha$ is related to the wavenumber of the incident transverse electric (TE) plane EM wave (in the free space) [31,37].

$$P_1 = \int_{ar_{12}}^{ar_{12}} \tau J_1(\tau)d\tau$$

$$P_2 = \int_{ar_{1}}^{ar_{1}} \tau J_1(\tau)d\tau$$

$J_1$ denotes the first-order Bessel function of the first kind.

The material-dependent phase term ($\Phi$) is defined as the real part of a complex fractional function.

$$\Phi = \Re\left(\frac{(\alpha_1 + \mu_0)(\alpha_1 - \mu_0) - (\alpha_1 + \mu_0)(\alpha_1 - \mu_0)e^{\alpha_1c}}{-(\alpha_1 - \mu_0)(\alpha_1 - \mu_0) + (\alpha_1 + \mu_0)(\alpha_1 - \mu_0)e^{2\alpha_1c}}\right)$$

$\mu_1$ and $c$ are the relative magnetic permeability and thickness of the magnetic plate. $\alpha_1$ is the square root of a complex term, which is related to the wavenumber of the transverse electric (TE) plane EM wave (in the steel) [31,38].

$$\alpha_1 = \sqrt{\alpha^2 + j2\pi\mu_1\mu_0 f}$$

$f$ is the working frequency of the exciting current.

B. Integration version of material-independent algorithm – inversion of lift-off distance

Generally, for a magnetic steel slab (unlike the non-magnetic materials), the eddy current is restrained around the surface of the sample even under the working frequency of 100 Hz (referring to the skin depth formula ($\pi \sigma \mu_0 f^{-1/2}$)). Owing to the eddy current skin effect, the magnetic slab can be treated as a conductive half-space. Therefore, $\Re(e^{2\alpha_1c}) \gg 1$ satisfies. Besides, $\Phi$ in (8) can be expressed as

$$\Phi = \Re\left(\frac{\alpha_1 - \alpha_1}{(\alpha_1 + \alpha_1)}\right)$$

For an eddy current sensor with moderate size (e.g. Table 1) the effective range of $\alpha$ is limited (according to Fig. 3, from 0 to 180 for the sensor in Table 1). That is, $2\pi\mu_1\mu_0 f \gg \alpha^2$ for the whole frequency range. Thus, (10) can be simplified as

$$\Phi = \Re\left(\frac{\alpha}{\alpha + \sqrt{2j2\pi\mu_1\mu_0 f^{1/2}}}\right)$$

As shown in Fig. 2, for the relatively high working frequencies (particularly frequencies exceed 400 kHz), it has been found $\Phi$ can be approximated with a linear function $T$.

$$T = \frac{\mu_1 - \alpha}{\pi \mu_0 f - 1}$$

In (12), the slope is related to material-dependent parameters $\mu_1$, $\sigma$, and the working frequency $f$. Thus, the inductance...
The inductance change from the transmitter-reference sensing winding - $L_2$ becomes,

$$L_2(\alpha) = KG \int_0^{2\alpha_{o}} e^{-\alpha(2\alpha+4h+3g)} \sin^2 \left( \frac{\alpha \pi}{2\alpha_{o}} \right) \frac{\mu_1}{\pi \mu_d} \alpha - 1 \, d\alpha$$

(20)

In (20), $G$ is the normalization term between $M_2$ and the sinusoidal function.

$$G = \frac{P_{g}}{\alpha_{o}} e^{ab}(e^{-ab} - 1)^2$$

(21)

Thus, the simplified version of (17) and (19) for (20) becomes,

$$F_2 = G \int_0^{2\alpha_{o}} e^{-\alpha(2\alpha+4h+3g)} \sin^2 \left( \frac{\alpha \pi}{2\alpha_{o}} \right) \frac{\alpha \pi}{2\alpha_{o}} \, d\alpha$$

(22)

$$Y_2 = G \int_0^{2\alpha_{o}} e^{-\alpha(2\alpha+4h+3g)} \sin^2 \left( \frac{\alpha \pi}{2\alpha_{o}} \right) \frac{\alpha \pi}{2\alpha_{o}} \, d\alpha$$

(23)

To eliminate the material-dependent term $\frac{\mu_1}{\pi \mu_d} Y_2$, the dual working frequencies $f_1$ and $f_2$ are considered.

$$\sqrt{f_1 f_2} (f_2 - \sqrt{f_1 f_2}) = K(\sqrt{f_1} - \sqrt{f_2})$$

(24)

In (22) and (23), assign,

$$X_2 = \alpha_{o} (2\alpha_{o} + 4h + 3g)$$

(25)

Then, after the integration, $F_2$ becomes,

$$F_2 = \frac{\pi^2 \alpha_{o} G (1 - e^{-2X_2})}{2X_2 (X_2^2 + \pi^2)}$$

(26)

Since $X_2 \gg 1$, the exponential term $e^{-2X_2} \ll 1$. Thus, $F_2$ becomes,

$$F_2 = \frac{\pi^2 \alpha_{o} G}{2X_2 (X_2^2 + \pi^2)}$$

(27)

Substitute (27) into (24), a simplified equation (without integration) for $X_2$ can be derived.

$$\frac{\pi^2 \alpha_{o} G}{2X_2 (X_2^2 + \pi^2)} = \frac{\sqrt{f_1 f_2} (f_2 - \sqrt{f_1 f_2})}{K(\sqrt{f_1} - \sqrt{f_2})}$$

(28)

Assume the solution of $X_2$ in the simplified equation (28) is $X_*$, then the lift-off distance can be derived according to equation (2).

$$l_0 = \frac{X_*}{2\alpha_{o} - \frac{4h + 3g}{2}}$$

(29)

### D. Lift-off insensitive inductance feature - measurement of relative magnetic permeability
is found
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restoration loop.

μswept-frequency inductance spectrum) closest to the lift-off
of

The change of the relative permeability in each iterative loop is,
from iterative loops [24]. The relative magnetic permeability can be restored
(29) with the corresponded frequency at the lift-off insensitive
derived lift-off distance from the transmitter-reference coil via
magnetic permeability can be measured by combining the
insensitive inductance, is
independent of different materials. For the sensor listed in Table
frequency. Besides, the corresponding inductance is
insensitive to the lift-off variation under a certain working
observed in Fig. 4, the inductance change
the magnetic permeability of the magnetic slab. As can be
seen in Fig. 4, the inductance change \( L_1 \) is found insensitive to the lift-off variation under a certain working
Besides, the corresponding inductance is independent of different materials. For the sensor listed in Table
the corresponding inductance, termed as the lift-off insensitive inductance, is \(-3.97 \times 10^{-10} \text{ H}\). Therefore, the
magnetic permeability can be measured by combining the
derived lift-off distance from the transmitter-reference coil via
(29) with the corresponded frequency at the lift-off insensitive
inductance. The relative magnetic permeability can be restored
from iterative loops [24].

\[
\mu_r = \Delta \mu_1 + \mu_r \quad (30)
\]

In (30), \( \mu_r \) is the reference relative magnetic permeability.
The change of the relative permeability in each iterative loop is,
\[
\Delta \mu_1 = \frac{1}{1^2} (L_0 - L_1(\mu_r f_{i0})) \quad (31)
\]

\( L_1 \) is the analytical inductance with the input of \( \mu_r \) and the
corresponded frequency \( f_{i0} \) at \( L_0 \). That is, the input frequency of \( L_1 \) can be referred from the frequency (according to the
swept-frequency inductance spectrum) closest to the lift-off insensitive inductance \( L_0 \). \( J \) is the inductance sensitivity around
\( \mu_r \).

\[
J = \frac{L_1(\mu_r f_{i0}) - L_1(\mu_r - \lambda \mu_r f_{i0})}{\lambda \mu_r} \quad (32)
\]

\( \lambda \) in (32) is a residual value, which is defined as 0.01 for the
restoration loop.

### III. Experiment

The predictions algorithms in (29) and (30) have been tested
with measurements on three different materials of magnetic
steels. The eddy current sensor is designed as three co-axial coil
windings (structure shown in Fig. 1). The transmitter is
equipped between the receiver (bottom) coil and reference (top)
coil with an identical separation gap \( g \). As listed in Table 1, the
radius of the receiver and the reference coil is designed larger
than that of the transmitter coil to fully receive the reflected
magnetic flux from the test piece. The measured inductance
from the transmitter-reference sensing pair is used for the
inversion of the lift-off distance via the simplified material-
indipendent algorithm in (28) and (29). Besides, the
system

![Fig. 4 Analytical inductance change from the transmitter-receiver sensing pair versus lift-off distance under different working frequencies a) DP 600 b) DP 800 c) Duplex stainless steel (in Table 2)](image)

Since the transmitter-receiver sensing pair is closer and
sensitive to the test material (compared to transmitter-
reference), its inductance value is used for the measurement of
the magnetic permeability of the magnetic slab. As can be
observed in Fig. 4, the inductance change \( L_1 \) is found insensitive to the lift-off variation under a certain working
Besides, the corresponding inductance is independent of different materials. For the sensor listed in Table
the corresponding inductance, termed as the lift-off insensitive inductance, is \(-3.97 \times 10^{-10} \text{ H}\). Therefore, the
magnetic permeability can be measured by combining the
derived lift-off distance from the transmitter-reference coil via
(29) with the corresponded frequency at the lift-off insensitive
inductance. The relative magnetic permeability can be restored
from iterative loops [24].

\[
\mu_r = \Delta \mu_1 + \mu_r \quad (30)
\]

In (30), \( \mu_r \) is the reference relative magnetic permeability.
The change of the relative permeability in each iterative loop is,
\[
\Delta \mu_1 = \frac{1}{1^2} (L_0 - L_1(\mu_r f_{i0})) \quad (31)
\]

\( L_1 \) is the analytical inductance with the input of \( \mu_r \) and the
(corresponded frequency \( f_{i0} \) at \( L_0 \). That is, the input frequency of \( L_1 \) can be referred from the frequency (according to the
swept-frequency inductance spectrum) closest to the lift-off insensitive inductance \( L_0 \). \( J \) is the inductance sensitivity around
\( \mu_r \).

\[
J = \frac{L_1(\mu_r f_{i0}) - L_1(\mu_r - \lambda \mu_r f_{i0})}{\lambda \mu_r} \quad (32)
\]

\( \lambda \) in (32) is a residual value, which is defined as 0.01 for the
restoration loop.

#### TABLE I

| Parameter                  | Transmitter coil | Receiver or reference coil |
|----------------------------|------------------|----------------------------|
| Inner radius \( t_{11} / t_{12} \) (mm) | 11.0             | 20.0                       |
| Outer radius \( t_{21} / t_{22} \) (mm) | 11.7             | 20.7                       |
| Turns \( N \)               | 7                | 7                          |
| Gap \( g \) (mm)            | 4.0              | 4.0                        |
| Height \( h \) (mm)         | 4.9              | 4.9                        |
| Lift-offs \( l_0 \) (mm)    | 1.0:1.0:12.0     |                            |

![Fig. 5 Measurement system](image)

In Fig. 5, the designed eddy current sensor is connected to
the impedance analyser. The measured inductance data is
exported to the PC via the USB interface cable. In equations
from (33) to (35), \( Z_a \) and \( Z_c \) denote the measured impedance
with and without (in the free space) the sample, respectively; \( L_a \)
and \( L_0 \) are the experimental inductance with and without (in
the free space) the sample, respectively; \( R_a \) and \( R_c \) are the mutual
resistance (real part of the impedance) caused by the sample and
coils, respectively; By using the inductance change equation in
(35) (which is corresponding to the analytical equations in 1 and
2), the ambient noise signals (including the mutual resistance
\( R_a \) and \( R_c \), or potentially high-frequency parasitic impedance
of the coils \( Z_c \) (35)) are excluded from the experimental
inductance change. Besides, the working frequency of the
impedance analyser is from 1 kHz to 5 MHz, which is much lower than the resonance frequency. Consequently, the proximity effect (with parasitic capacitance) barely exists during the measurement. Frequencies lower than 1 kHz will result in a relatively poor Signal-to-Noise Ratio (SNR).

As listed in Table 2, the magnetic steels are (ferrite-austenite) alloys with different ferrite fractions. Since the thickness of the steel slab is much larger than the skin depth, the samples can be treated as the half-space (and the skin effect exists) under the whole frequency range. Therefore, the phase term \( \phi \) in (8) can be approximated by (10), which is independent of the sample thickness.

### TABLE II

| Parameters of Magnetic Steels | DP 600 | DP 800 | Duplex stainless steel |
|------------------------------|--------|--------|------------------------|
| Thickness (mm) \( t \)       | 4      | 4.3    | 6.45                   |
| Relative permeability \( \mu \) | 222    | 144    | 45                     |
| Electrical conductivity \( \sigma \) (MS/m) | 4.13   | 3.80   | 1.30                   |

**IV. RESULT AND DISCUSSION**

#### A. Swept-frequency inductance

The swept-frequency inductance change (due to the test steel) from both the transmitter-receiver and transmitter-reference sensing pairs are shown in Fig. 6 a) and b). As the frequency increases, the inductance curve begins with a positive value then gradually decreases to a negative one. Besides, the inductance curve of one sample with different lift-off distances will converge at one point, where the measured inductance is shown less affected by the lift-off distance. As the frequency further increases, the inductance curve of one sample with different lift-off variations will gradually diverge. However, the inductance curve for one lift-off distance but different samples will gradually converge, where the inductance is shown sensitive to the lift-off distance but less sensitive to the test sample due to the restrained eddy current under the skin effect. Thus, the lift-off distance of the sensor is inversely from the sample due to the restrained eddy current under the skin effect.

### Fig. 6 Swept-frequency inductance for the sensor above the magnetic slab with lift-off distance of 2, 4, and 6 mm a) transmitter-receiver sensing pair b) transmitter-reference sensing pair

#### B. Inversion of lift-off distance using simplified material-independent algorithm

### Fig. 7 Inductance for the sensor above the magnetic slab with different lift-off distances under the working frequency of 5 MHz a) transmitter-receiver sensing pair b) transmitter-reference sensing pair

Fig. 7 shows the inductance change from both the transmitter-receiver and transmitter-reference sensing pairs at different lift-off distances under the working frequency of 5 MHz. It can be observed that, due to the significantly restrained eddy current under the skin effect, the inductance of different lift-off distances is less influenced by the test steel, particularly when the lift-off distance reaches 12 mm. As shown in Fig. 2,
under the high working frequencies, the material-dependent phase term $\Phi$ approaches -1. Thus, with the increased working frequency, the test steel gradually becomes a pure inductive material. Besides, the inductance is less affected by the parameters of the material, as can be referred to equation (12).

889.57 kHz – 5.00 MHz and 3.16 MHz – 5.00 MHz (can be referred to Fig. 9 – the error of the lift-off inversion).

Fig. 9 Error of the inversion for the lift-off distance from the inductance of different dual-frequency combinations when the test piece is a) DP 600 b) DP 600 c) Duplex stainless steel

In Fig. 9, the lift-off inversion is shown to be more affected by different samples under low dual-frequency combinations, especially for the dual-frequency combination of 50.06 kHz – 112.05 kHz, where the phase term $\Phi$ in (12) (Fig. 2) is more influenced by the parameter $\mu_1$ and $\sigma$. Considering the accuracy, the inversed lift-off under the dual-frequency combinations of 3.16 MHz – 5.00 MHz is selected for the further inversion of the magnetic permeability (with a maximum error of 0.24 mm).
C. Inversion of magnetic permeability based on the feature - lift-off insensitive inductance

As the transmitter-receiver sensing pair is closer and more sensitive to the test steel, the inductance $L_0$ is used for the inversion of the relative magnetic permeability. Fig. 10 depicts $L_1$ versus lift-off distances under different working frequencies. It can be observed that for one sample, the inductance change is shown to be less affected by the lift-off distance, termed as the lift-off insensitive inductance. Moreover, inductance curves of different samples share the same lift-off insensitive inductance $L_0$ (around $-3.97 \times 10^{-11}$ H). From the swept-frequency inductance in Fig. 6 a), the corresponding frequency of the inductance closest to the lift-off insensitive inductance $L_0$ are 46.63, 32.87, and 27.78 kHz for DP 600, DP 800, and Duplex stainless steel.

Parameters including the inverted lift-off distance, lift-off insensitive inductance $L_0$ and its corresponded frequency are used for the inversion of the relative magnetic permeability of the steel using iterative equations from (30) to (32). In Fig. 11, with the inverted lift-off distance (material-independent), lift-off insensitive inductance benchmark ($L_0 = -3.972 \times 10^{-11}$ H – data tips in in Fig. 10), and corresponded frequencies $f_{L_0}$ (46.63, 32.87, 27.78 kHz for DP 600, DP 800, and Duplex stainless steel – legend of Fig. 10 or data tips in Fig. 6), the relative magnetic permeability can be accurately restored with a maximum error of 0.6 % at the lift-off distance of 12 mm. Besides, the error is nearly independent of different ferrite-austinite steels.

V. CONCLUSION

In this paper, two algorithms have been proposed for the inversion of both the lift-off distance and magnetic permeability of the steel. For the inversion of the lift-off distance, a simplified algorithm (without redundant integration) has been explored, which therefore can be used for the online measurement. With the inductance of transmitter-reference sensing pair, the inverted lift-off distance is shown to be material-independent. From the experiments on three different magnetic alloys, the lift-off distance is verified can accurately restore the lift-off distance, with a maximum error of 0.24 mm at 12 mm. Moreover, the restored lift-off distance is implemented for the inversion of magnetic permeability using iterative algorithms. Based on the lift-off insensitive inductance feature (which is independent of the test sample and less affected by the lift-off) of the transmitter-receiver sensing pair (closer and sensitive to the test piece) and its corresponded frequency (sensitive to sample and insensitive to lift-off distance), the error of the restored permeability can be controlled within 0.6 % for the lift-off distance up to 12 mm.

ACKNOWLEDGEMENT

This work was supported by [UK Engineering and Physical Sciences Research Council (EPSRC)] [grant number: EP/P027237/1] [title: Real-time In-line Microstructural Engineering (RIME)].

Author Contributions: (Methodology, manuscript drafting) M. Lu and X. Meng; (conceptualization, manuscript revision) M. Lu; (experiment data curation, manuscript review) M. Lu, R. Huang, L. Chen; (Supervision) W. Yin, A. Peyton, M. Lu. All authors have read and agreed to the published version of the manuscript.

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