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Kinetic Modeling of Heat and Mass Transfer During Deep Fat Frying of Churro

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Abstract: The effect of deep fat frying temperatures, ranging from 160 to 190 °C, on frying parameters including the heat transfer coefficient (h_e), mass transfer coefficient (k_e) and effective moisture diffusivity (D_e) were investigated during deep fat frying of churro that was fried as dough pastry. Therefore experimental studies were conducted for both heat and mass transfer phenomena and mathematical model was developed for simultaneous transfer by using Newman technique for churro actual geometry (3-D cylindrical shape). Fourier's and Fick's laws were applied for the computation of coefficients of heat and mass transfer. The h_e coefficients were 437.360-93.535 W/m^{2}K in the temperatures range of 160 to 190 °C. However, the value of k_e and D_e increased by an increase in oil temperature during frying. The maximum values were determined as 17.36×10^{-5} m/s and 2.48×10^{-5} m^2/s at 190 °C for k_e and D_e, respectively. Model and experimental data had good agreement and the transfer coefficients followed the first order kinetic model with high R^2 and low root mean square error (RMSE) values. The Arrhenius equation was applied to describe the relationship between the effective moisture diffusivity and deep fat frying temperature, so the value of activation energy was calculated as 63.546 kj/mol.

Keywords: Biot number, first-order kinetic, frying process, heat transfer coefficient, moisture diffusitivity, newman technique.

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1. INTRODUCTION

Churro, the traditional Spanish dessert, is a kind of sweet snack and it is very popular in Spain and Mexico. It is prepared from soft dough which was formed strips by a simple extruder and generally fried between 185-200 ˚C at 3-4 minutes until golden color and the crispy product is obtained (Morales et al., 2008; de Oliveira Silva et al., 2022). After the frying process is completed, Spanish churros are generally coated in sugar or cinnamon powder and served with thick dipping chocolate (Moolwong, 2020). Deep-fat frying or immersion frying is an important process for the preparation of churro in which heat and mass transfer occur simultaneously (Safari et al., 2018). Heat is transferred from the oil to the food surface by convection and then to the core by conduction, and at the same time, water loss by evaporation and absorption of oil by the churro is a complex process (Oke et al., 2018). This complex operation brings about desirable physical, chemical, structural and nutritional changes such as gelatinization of starch, the denaturalization of proteins, inactivation of enzymes, destruction of microorganisms, Maillard reaction, aromatization, shrinkage, etc. (Dourado et al., 2019; Manjunatha et al., 2019). Thanks to the beneficial effect of these physicochemical changes, the most acceptable properties of churro such as golden color, crispy and crunchy crust, soft and moist interior, cylindrical shape, and fine texture are obtained. Moreover, suitable design, control, and optimization of the frying operation are essential to obtain a high-quality product (Dehghannya and Ngadi, 2021). For this reason, knowledge of the frying parameters including h_e, k_e, and D_e are necessary to predict the quality of product and standardize and optimize processing conditions. Several researches of determining heat and mass transfer parameters by different techniques for model foods are presented in the literature. For example, Neethu et al. (2016), developed a simple model to calculation of heat and mass transfer parameters for fried pantoa (Indian dairy dessert), at 125–145 °C. When the frying temperature increased from 125 to 145 °C, the h_e parameter increased from 101.77 to 237.10 W/m^{2}K, while the k_e parameters increased from 7.79×10^{-6} to 9.05×10^{-6} m/s. Sandhu et al., (2016), determined the h_e coefficient for a fried-potato disc with one-dimensional methodology. The h_e parameters were 3617, 4517, and 7307 W/m^2°C at frying temperatures of 150, 170, and 190

°C, respectively. Another investigation was carried out to examine mass transfer parameters for fried green peas (Manjunatha et al., 2019). The kinetic rate constant for moisture loss and as the oil uptake was increasing with increasing the frying temperature.

The reported results showed that there is a lack of knowledge on the calculation of coefficients of heat and mass transfer, accurately. Because heat transfer was evaluated without mass transfer and also the actual dimensions of the food product (3-D) were not taken into account in the modeling studies. Since heat and mass transfer during frying are interrelated, they both need to be considered when investigating the frying process. In addition, using simple geometry rather than the real food geometry may confuse the calculation of kinetic boundary conditions.

In this research, therefore, the kinetics of heat and mass transfer coefficients of the churro with actual geometry during the frying process at four different temperatures (160, 170, 180, and 190 °C) were investigated. There is no scientific literature about the frying kinetic parameters of the churro. For this reason, the aim of this research was to determine the kinetics of convective heat transfer, mass transfer, and effective moisture diffusivity parameters during the frying process. To reach this aim, the plots of dimensionless temperature and concentration ratios against frying time were used to define the parameters with churro geometry (3-D cylindrical shape). Another objective of the present investigation is modeling the frying kinetic parameters. Thus, the kinetic model helps to establish the connections between phases and processing time.

2. MATERIAL AND METHOD

2.1. Preparation of Churro Dough

The main ingredients of churro dough were water 250 g, butter 47 g (Torku), salt 0.5 g (Billur) and wheat flour 300 g (Type 850, Yüksel) (de Oliveira Silva et al., 2022).
When all the ingredients were ready, water, butter, and salt were mixed and boiled and wheat flour was added to the water. After cooling, the dough was filled into the piping bag and squeezed into the hot oil using a star-shaped piping nozzle which is a symbol of churro. Acylindrical shape was given to dough (10 cm in length, 1 cm in diameter) and then fried (Moolwong, 2020).

2.2. Deep Fat Frying of Churro

Deep fat frying of churro was carried out using a deep fryer (Angelo Po, Italy). The frying temperatures and times were selected as 160, 170, 180 and, 190 °C at 420, 360, 300 and 180 s, respectively. Fried samples were filtered for 1 minute and placed on an adsorbent paper to remove surface oil.

2.3. Proximate Composition for Thermophysical Properties

Thermophysical properties of churro such as thermal conductivity (k), density (p) and specific heat (c_p) are necessary to determine the h_e parameter. For this, there are certain improved equations (Eq.1-3) (Cemeroğlu, 2017) and it is necessary to know the proximate composition of churro in using these equations. The moisture, protein, crude fat and ash of churro dough were determined by AACC methods (AACC, 1999). The total carbohydrate content was calculated via subtraction of the sum of moisture, protein, crude fat and ash from 100. These thermophysical parameters assumed constant during the frying.

$$\mathrm{k} = \sum \mathrm{k_i} \ \mathrm{x} \ \mathrm{X_{Vi}} \tag{1}$$

$$\rho = \frac{X_i}{\rho_i} \frac{1}{\frac{X_C}{1600} + \frac{X_P}{1320} + \frac{X_F}{920} + \frac{X_A}{240} \frac{X_W}{1000}} \tag{2}$$

$$\mathrm{Cp} = 1.6\mathrm{X_C} + 2.0\mathrm{X_P} + 2.0\mathrm{X_F} + 1.1\mathrm{X_A} + 4.2\mathrm{X_W} \tag{3}$$

2.4. Experimental Study and Kinetic Modeling for Heat Transfer

The inner temperatures of the churro doughs during frying at different temperature-time combinations and also the temperature of the frying oil were measured by a K type thermocouple, for 1 s time interval. These thermocouple sensors were connected to a data logger (Sper Scientific, Scottsdale) and obtain temperature-time graphs with using software program of data logger.

The Fourier's equation for an infinite plane wall (Eq. 4) and the Fourier's equation for an infinite cylinder shape (Eq.5) provides a simplified description of the heat transfer during frying. According to Newman technique, the Eq. (4) and Eq. (5) can be used together to obtain the solution of experimental heat transfer data for the churro geometry (finite cylindirical shape) by making use of the superimposition technique (Eq. 6).

$$Y_z = \frac{T_{(z,t)} - T_\infty}{T_i - T_\infty} = \sum_{i=1}^{\infty} \frac{2 \sin \mu_i}{\mu_i + \sin \mu_i \cos \mu_i} \exp\left(-\mu_i^2 \frac{\alpha t}{L^2}\right) \cos\left(\mu_i \frac{z}{L}\right) \tag{4}$$

$$Y_r = \frac{T_{(r,t)} - T_\infty}{T_i - T_\infty} = \sum_{\mathrm{i}=1}^{\infty} \frac{2\beta_\mathrm{i}}{(\mathrm{Bi_r}^2 + \beta_\mathrm{i}^2)} \frac{1}{\left(J_0(\beta_i)\right)^2} J_1(\beta_i)\, J_0(\beta_{in_r}) \exp\left(-\beta_i^2 \frac{\alpha t}{R^2}\right) \tag{5}$$

$$\mathrm{Y}rz = \mathrm{Yz} \times \mathrm{Y}r \tag{6}$$

$$Y_{0zr} = \frac{T_{0zr} - T_\infty}{T_i - T_\infty} = \frac{2Bi_r}{(Bi_r^2 + \beta_i^2) J_0(\beta_i)} \, exp\left(-\beta_i^2 \frac{\alpha t}{R^2}\right) \frac{2 \sin \mu_1}{(\mu_{1+} \sin \mu_1 \cos \mu_1)} \, exp\left(-\mu_1^2 \frac{\alpha t}{L^2}\right)$$

The first order exponential kinetic model was used to describe the h_e parameters for different frying temperatures.

$$h_t = h_e + (h_0 - h_e) e^{-k_h t} \tag{7}$$

where h_0, h_t, h_e are the heat transfer parameters of initial, at time t and at equilibrium respectively and k is kinetic coefficient and t is frying time.

2.5. Experimental Study and Kinetic Modeling for Mass Transfer

Experimental study was conducted of mass transfer with the calculation of moisture contents for fried churro samples by dry matter analysis at 135 °C (AACC, 1999). Fick's second law equation for an infinite plane wall (Eq. 8) and an infinite cylinder shape (Eq. 9) provide a description of the moisture loss during frying. Eq. (8) and Eq. (9) can be used together to obtain the solution of the experimental moisture content data for the churro geometry with the superimposition technique (Eq. 10).

$$C_z = \frac{C_{(z,t)} - C_\infty}{C_i - C_\infty} = \sum_{i=1}^{\infty} \left(\frac{2 sin\mu_i}{\mu_i + sin\mu_i \, cos\mu_i}\right) \exp\left(-\mu_i^2 . \frac{D_e . t}{L^2}\right) \cos\left(\mu_i \frac{z}{L}\right) \quad (8)$$

$$C_r = \frac{C_{(r,t)} - C_\infty}{C_i - C_\infty} = \sum_{i=1}^{\infty} \frac{2\beta_1}{(Bi_{r^2} + \beta_1{}^2)} \frac{1}{((J_0(\beta_1))^2} J_1(\beta_1) J_0\left(\beta_1 \frac{r}{R}\right) \exp\left(-\beta_1{}^2 \frac{D_e t}{R^2}\right) \quad (9)$$

Crz=Cz×Cr (10)

$$C_{0zr} = \frac{C_{0zr} - C_\infty}{C_i - C_\infty} = \sum_{i=1}^{\infty} \left(\frac{2 sin\mu_i}{\mu_i + sin\mu_i cos\mu_i}\right) \left(\frac{2Bi_r}{(Bi_{r^2} + \beta_{i^2}).J_0(\beta_i)}\right) exp - \left(\frac{\beta_{i^2}}{R^2} + \frac{\mu_i{}^2}{L^2}\right) D_e . t$$

The first-order reaction kinetic model describe the k_e and D_e values for different frying temperatures (Eq. 11 and Eq.12).

$$X_t = X_e + (X_0 - X_e) e^{-k_x t} \quad (11)$$

$$Y_t = Y_e + (hDe_0 - De_e) e^{k_h t} \quad (12)$$

3. RESULTS AND DISCUSSION

3.1. Kinetic Model of Heat Transfer Phenomena

The chemical composition and thermophysical properties of the churro dough are given in Table 1. In order to determine the convective heat transfer coefficients for all frying temperatures, firstly, the time-temperature profiles of the churros were obtained experimentally (Fig. 1). In Figure 1, the experimental study resulted in a slight increase in temperatures towards the boiling point of the water in the center of the churros during approximately the first 100 s of the frying process and then remained constant. The h_e parameters were 437.36, 301.679, 123.256, and 93.535 W/m^2 K at 160, 170, 180 and 190 °C, respectively. It is evident that the heat transfer coefficient and Biot numbers decreased with an increase in frying temperature. This result indicates that a higher temperature frying environment results in higher water loss from the product.

Table 1. Chemical composition and thermophysical properties of churro

Nutrient	Amount(%)	Property	Value
Moisture	60.425	Thermal conductivity, *k*	0.497 W/m °C
Protein	5.252	Specific heat, c_p	3.038 kj/kg °C
Fat	0.101	Density, *p*	1173.014 kg/m³
Ash	0.351	Thermal diffusivity ,α	1.394×10^{-7} m²/s
Carbohydrate	33.871		

The greater the rate of water loss, the greater the amount extracted from the incoming energy. This will reduce the amount of energy available for the internal energy increase and consequently the effective heat transfer coefficient will decrease (Yıldız et al., 2007; Erim Köse and Dogan, 2018). These results were in agreement with the findings of Yıldız et al. (2007) for french fries, Erim Kose and Dogan (2018) for tulumba dough, and Franklin et al. (2014) for gulab jamun. On the other hand, the data obtained in the study contradict most of the other studies in the literature, which found that the convection heat transfer coefficient increased with the increase in frying oil temperature (Seruga and Budžaki, 2004; Neethu et al., 2016; Sandhu et al., 2016; Koerten et al., 2017;, Asefi and Roufegarinejad, 2021). This difference could be attributed to the heat transfer was not evaluated with mass transfer simultaneously, product shape and porosity were not actual dimensions of the food product (3-D), and different frying conditions used in these studies.
In addition, the changes in the h_e parameters were best represented by the first-order kinetic model with a good fit obtained by nonlinear regression (R^2=0.9576 and RMSE=0.082). The kinetic rate constant (k) was also calculated for all the frying parameters (Table 3). The negative k value (-0.0552) showed no strong frying temperature dependence, which greater values measured at increased with decreasing the frying temperature.

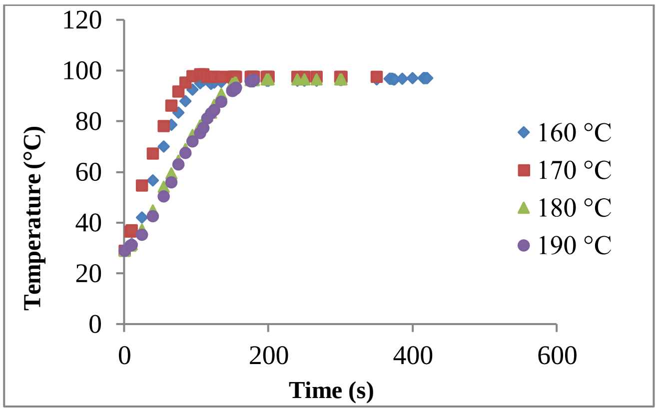

Figure 1. Experimental values for the temperature profiles of churro

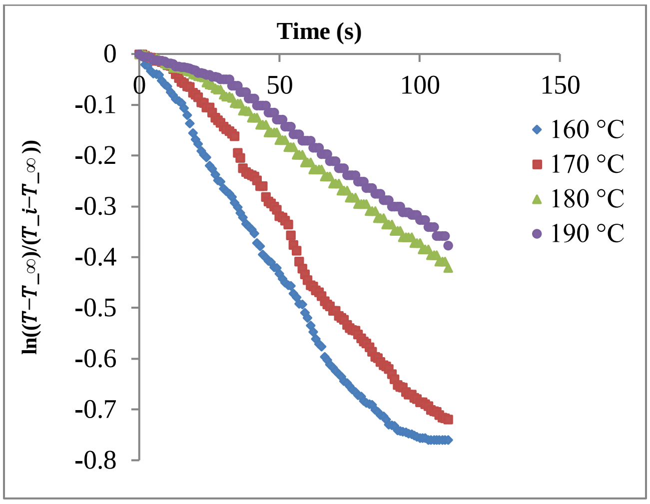

Figure 2. Dimensionless temperature ratio versus time

3.2. Kinetic Model of Mass Transfer Phenomena

Moisture loss is the major mass transfer phenomena during frying operation. The speed of frying operation is closely interested in the combination of frying time and temperature (Ngadi et al., 2006; Nasiri et al., 2011). The data of moisture contents were fitted to Fick's second law of diffusion and the first-order kinetic model, respectively, and the obtained model parameters are shown in Table 2.

Table 2. Biot numbers and frying parameters of churro

T (°C)	Biot number heat transfer	h_e W/ m^2°C	Biot number mass transfer	k_e×10^{-5} m/s	D_e×10^{-5} m^2/s
160	Bi_z=44.00 Bi_r=8.80	437.36	Bi_z=0.09 Bi_r=0.018	0.75	1.350
170	Bi_z=30.35 Bi_r=6.07	301.679	Bi_z=0.245 Bi_r=0.049	1.11	5.439
180	Bi_z=12.40 Bi_r=2.48	123.256	Bi_z=0.275 Bi_r=0.055	1.40	7.700
190	Bi_z=9.41 Bi_r=1.88	93.535	Bi_z=9.41 Bi_r=1.88	2.48	17.360

In order to obtain the model parameters, first, experimental studies were carried out. The experimental results of moisture contents at different frying temperatures have been reported in Fig 3. According to Figure 3, there was a fast decrease in all frying temperatures even in the first minutes due to the loss of water in surfaces of churros. The initial moisture content of churros was about 60.425 % (on wet basis, wb), and it was reduced to 35.43, 30.43, 28.73, and 27 % wb at temperatures 160, 170, 180, and 190 °C respectively. Similar results for different fried foods were reported by many researchers in the literature (Mariscal and Bouchon, 2008, Manjunatha et al., 2019, Adedeji et al., 2009, Zhang et al., 2020).

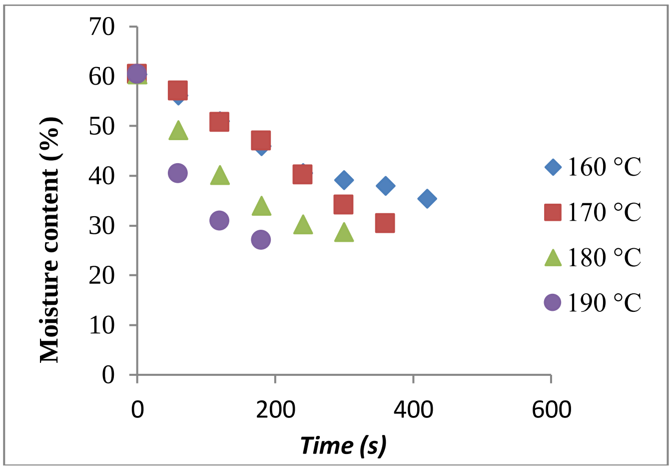

Figure 3. Moisture contents of churro for different frying temperatures

The kinetic data were obtained with the plots of dimensionless concentration ratio against frying times for different frying temperatures. D_e , k_e, and Biot numbers for mass transfer were determined from Figure 4.

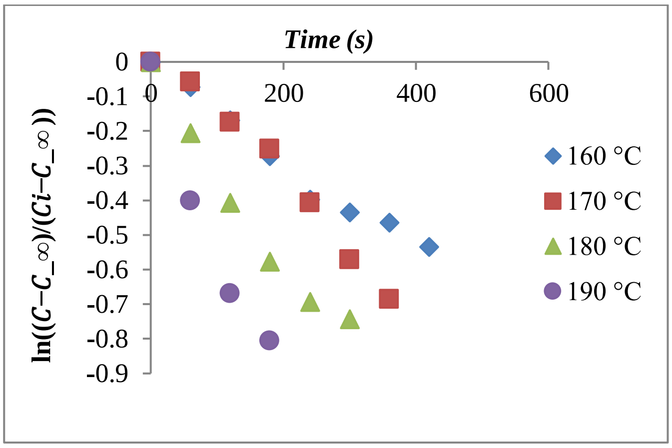

Figure 4. Dimensionless concentration ratio versus time

The D_e values of the frying processes at 160, 170, 180 and 190 °C were 0.75×10^{-5}, 1.11×10^{-5}, 1.40×10^{-5} ,2.48×10^{-5} m^2/s, respectively. This result revealed that the frying temperature had a favorable effect on the moisture diffusivities due to accelerating the moisture loss of the product. As deep-fat frying temperature increased, the moisture transfer coefficients also increased linearly from 1.35×10^{-5} to 17.36×10^{-5} m/s, indicating that maximum diffusion of moisture occurred at 190 °C. Similar results were reported on frying of the breaded fish nuggets (Zhang et al., 2020), krostula dough (Budzaki and Seruga, 2005), tulumba dough (Erim Köse and Dogan, 2008), green peas (Manjunatha et al., 2019), chicken nuggets (Adedeji et al., 2009). Torres-Gonzalez et al., (2018), reported that difusivity and mass transfer coefficients of Arepa Con Huevo increased with the increasing temperatures and its activation energy was calculated at 63.96 kJ/mol. Kinetic modeling for mass transfer of breaded and battered of fish nuggets during deep-fat frying was performed by Fick's second law and first order kinetic model (Yuan et al.,2018). Catillo et al. (2021), determined the kinetics of moisture loss for chorizo during atmospheric and vacuum frying with Fick's second law for cylinder geometry. The diffusion coefficient increased from 3.50×10^{-8} to 4.28×10^{-8} with increasing temperature for vacuum frying.

The linear relationship between ln (C/C_0) and frying time showed that the changes of effective mass transfer coefficient and moisture diffusivity followed first-order kinetics with high R^2 (0.9417-0.9726) and low RMSE (0.048-0.059) values (Table 3). An Arrhenius equation was used for described of the relationship between the frying temperature and moisture diffusivity (Fig 5). As shown in Fig.5, the slope was equal to the ratio of the activation energy and the universal gas constant and so activation energy was calculated as 63.546 kJ/mol. This result is in agreement with those reported by Mondal and Dash (2017), who found similar activation energy was 67.163 kJ/mol of fried Chhena Jhili, which is a popular deep fat frying dessert in India.

Table 3. Kinetic parameters of frying coefficients

Parameter	Model	k (s^{-1})	R^2	RMSE
h_e	First-order kinetic	-0.0552±0.026	0.9576	0.0821
k_e	First-order kinetic	0.0801±0.104	0.9417	0.0480
D_e	First-order kinetic	0.0382±0.051	0.9726	0.0590

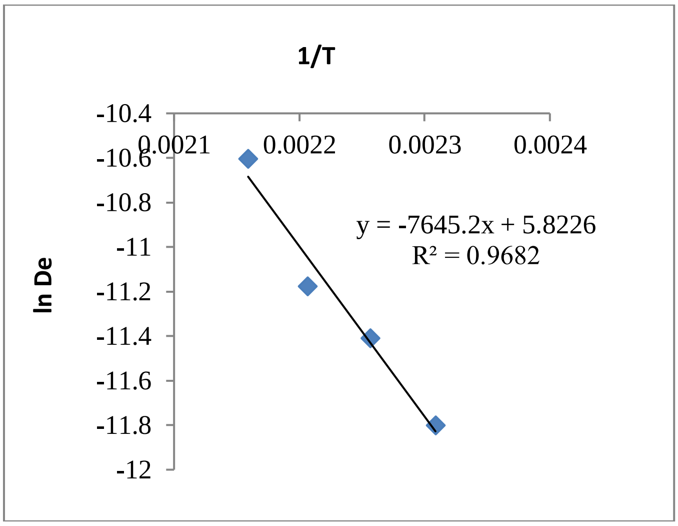

Figure 5. An Arrhenius relationship between temperature and moisture diffusivity

4. CONCLUSIONS

The frying process of churro was investigated for different time-temperature combinations on heat and mass transfer parameters in this study. An experimental study was conducted in the laboratory and the obtained data were analyzed kinetically. For this reason, analysis of the experimental data using the Fourier's and Fick's second law equations for churro geometry shape revealed that the heat transfer coefficient decreased, while the moisture diffusivity and moisture transfer coefficient increased linearly with frying temperature. The first-order kinetic models gave a good fit for all off frying parameters and the Arrhenius plot showed the temperature dependency of mass diffusion in the product. Thanks to this study, knowledge of heat and mass transfer parameters during the frying process accurately will assist in the equipment and process design of churros and similar fried foods. At the same time, thanks to the data obtained as a result of the study, the connection between the phases and the processing time can be established.

Ethics Committee Approval
N/A

Peer-review
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Author Contributions
All authors have read and agreed to the published version of manuscript.

Conflict of Interest
The authors have no conflicts of interest to declare.

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