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Research article

Radiation Dose and Image quality of coronary CT angiography performed with whole-heart coverage CT scanner with 0.25s rotation time in patients with irregular heart rhythm

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A B S T R A C T

Objectives: To evaluate radiation exposure, image quality, and diagnostic performance of coronary CT angiography (CCTA) using the invasive coronary angiography (ICA) as the reference standard in patients with irregular heart rhythm on a 0.25 s rotation time, 16 cm coverage, single-beat, CT scanner with AI-assisted motion correction.

Methods: CCTA data-sheets of 427 patients using a CT scanner with an ECG monitoring system and motion correction algorithm were collected retrospectively. All the patients were divided into two groups: regular heart rhythm (357 patients) and irregular heart rhythm (70 patients). 22 patients in irregular heart rhythm underwent ICA. Image quality and effective dose in both groups were evaluated and compared. Image quality was evaluated on 5-point scales. The diagnostic performance of CCTA in irregular heart rhythm group was compared with the results of ICA.

Results: The image quality in both groups was similar (4.34 ± 0.47 vs 4.37 ± 0.48, $p > 0.05$). No significant difference was observed in effective dose between two groups (2.7 ± 0.7 vs 2.9 ± 1.3, $p > 0.05$). The diagnostic accuracy was 90.91% in a patient-based analysis, 96.97% in a vessel-based analysis, and 98.61% in a segment-based analysis. In irregular heart rhythm group, gender was an important factor affecting the number of CCTA scans in a single examination and the radiation dose exposed to the patient.

Conclusions: For patients with irregular heart rhythm, a CT scanner with an ECG monitoring system and motion correction algorithm can not only reduce the radiation dose to the same level as patients with normal heart rhythms, but also ensure that the images with high diagnostic accuracy.

1. Introduction

Coronary computed tomography angiography (CCTA) is a widespread and reliable tool to evaluate coronary artery disease (CAD) [1,2]. Coronary CTA examination methods are mainly divided into prospective electrocardiogram (ECG)-triggered monitoring scan and retrospective ECG-gated scan [3]. Prospectively ECG-triggered CCTA could reduce radiation exposure compared to retrospectively gated CCTA [4]. The heart rate has a very significant impact on coronary CTA [5]. Irregular heart rhythm may lead to a decrease in

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image quality, higher radiation and contrast medium, and more frequent CCTA examinations for one patient [6–8]. To reduce the influence of irregular heart rhythm on CCTA, several advanced technologies have been applied into clinical application. Wide-detector CT with whole heart coverage and high rotation speed could provide high temporal and spatial resolution, and the motion-correction algorithm could further reduce motion artifacts [9,10]. However, irregular heart rhythm is still a challenge for CCTA imaging [11]. The CCTA of patients with irregular heart rhythms may fail due to abnormal heart rhythm fluctuations, resulting in increasing number of scans and then radiation dose received by the patient [12]. Recently, a scanner with 0.25s rotation time and a new generation of AI-based motion correction algorithm to improve image quality was introduced. With the help of high rotation time, once the ECG monitoring system detects the occurrence of arrhythmia, it will immediately stop scanning, and then start the next scan within the shortest time allowed by the system conditions. A clinical study has showed that the image quality of CCTA for patients with heart rate $\geq$75 bpm using this scanner could meet the criteria for diagnosis [13]. However, no clinical study assessed its radiation dose and diagnostic performance for patients with irregular heart rhythm.

The purpose of our study was to evaluate radiation exposure, image quality, and diagnostic performance of CCTA by using invasive coronary angiography (ICA) as the reference standard for patients with irregular heart rhythm.

2. Material and methods

2.1. Patient characteristics

This retrospective study was approved by the Ethics Committee of Shanghai Zhongshan Hospital (Fudan University, Shanghai, China), and written informed consent was obtained from all participants. The study design is shown in Fig. 1. In this study, a total of 427 consecutive patients (252 men and 175 women; age, 60.9 $\pm$ 13.3 years) who underwent prospective ECG-triggered CCTA between March and July 2021 were retrospectively enrolled. 357 patients were with normal sinus rhythm and 70 patients were with irregular heart rhythm. In irregular rhythm groups, 40 patients were with atrial fibrillation (AF), 18 patients were with ventricular premature beat, and 12 patients were with atrial premature beat. Twenty-two patients underwent the ICA within one to twenty-three days after CCTA examination. The scan times and effective dose were recorded and compared. No patients were excluded. The patient characteristics were shown in Table 1.

2.2. CCTA image acquisition

All CCTA were performed on a wide-detector CT (uCT960+, United Imaging Healthcare, Shanghai, China) with the following characteristics: 200 mm field of view (FOV), 512 $\times$ 512 matrix, 0.25s rotation. Firstly, all patients underwent non-enhanced CT for calcium scoring (120 kV, 24 mAs) at 75% of the R–R interval. Then, the contrast medium (Iopamidol, 370 mg iodine/ml, Bayer) was administered intravenously in dose of 0.7 mL/kg at a rate of 6 mL/s, followed by 20–30 mL of saline solution. Prospective ECG-triggered CCTA acquisition was performed with 100 kV and 120 mAs in one single heartbeat, using the bolus tracking technique for the start of scanning. The region of interest (ROI) was placed in the descending aorta, and the threshold was 120HU. The scan was started 6 s later after the threshold. All patients were scanned using an ECG monitoring system (Fig. 2). The acquisition phases were 30%–80% of the R–R cycle for all patients to ensure that images collected met the requirements of diagnosis. The CCTA images were reconstructed using the hybrid iterative reconstruction algorithm (KARL, United Imaging Healthcare) with the level of 5 at the best cardiac phase.

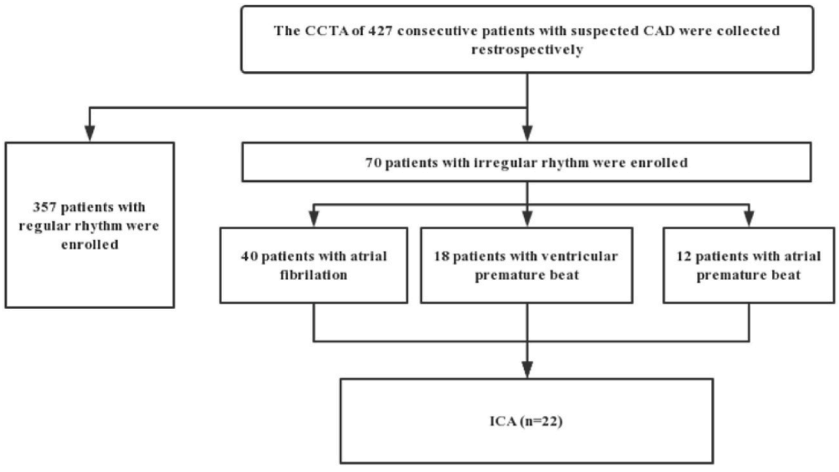

Fig. 1. Flowchart for 427 patients with suspected CAD (357 patients were with regular rhythm and 70 patients were with irregular rhythm). 22 patients in irregular heart rhythm underwent ICA.

Table 1
Patient characteristics.

	Total	Regular rhythm	Irregular rhythm	*p* value
Number	427	357	70	/
Age	61.5 ± 12.6	60.3 ± 12.8	67.7 ± 10.0	$p < 0.01$
Gender (men/women)	252/175	215/142	37/33	$p = 0.35$
Height(cm)	165.9 ± 8.6	166.0 ± 8.6	165.0 ± 8.6	$p = 0.46$
Weight(kg)	67.6 ± 12.6	67.6 ± 12.8	67.3 ± 11.7	$p = 0.77$
BMI (kg/m^2)	24.4 ± 3.4	24.4 ± 3.4	24.6 ± 3.2	$p = 0.73$
Heart rates (beat per minute):				
Minimal heart rate	63.1 ± 11.3	63.8 ± 10.8	59.1 ± 13.8	$p < 0.01$
Maximal heart rate	80.5 ± 22.1	73.9 ± 11.8	114.3 ± 30.6	$p < 0.01$
Mean heart rate	69.1 ± 14.1	67.0 ± 10.9	79.6 ± 21.9	$p < 0.01$

Data are expressed either as number (n) or as mean ±standard deviations.
BMI: body mass index.

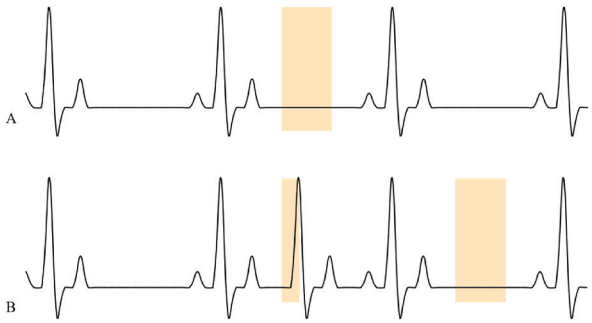

Fig. 2. Diagram of coronary CT angiography with an ECG monitoring system to avoid the influence of heart rhythm fluctuations on scanning. (A) Coronary CT angiography of regular heart rhythm. (B) Coronary CT angiography of irregular heart rhythm. During the first scan, the system terminated the scan when detecting the occurrence of an abnormal heart rhythm, and then performed the scan again in the next cardiac cycle.

2.3. CCTA image reconstruction

The reconstructed parameters of CCTA images were as follows: slice thickness of 0.5 mm and interval of 0.5 mm for coronary artery evaluation, C_SOFT_AA kernel, and 8 level of iterative reconstruction (KARL, United Imaging Healthcare). The reconstruction phase of CCTA images was decided by a software for the automatic identification of the best cardiac phase.

2.4. Subjective image quality assessment

All CCTA images were analyzed using commercial workstation (uWS-CT, R004, United Imaging Healthcare, Shanghai, China). Two radiologists blinded to patient information and acquisition parameters evaluated the image quality per patient. Image quality score was assessed by using a 5-point Likert scale (5: excellent, no artifacts; 4: good, minor artifacts, good diagnostic quality; 3: adequate, moderate artifacts and acceptable for routine clinical diagnosis; 2: poor, severe artifacts impairing accurate evaluation; 1: non-diagnostic).

2.5. Coronary stenosis

The degree of stenosis in all segments on CCTA for patients in this study who underwent ICA were evaluated by a third radiologist, and the result of ICA was regarded as the standard reference. The degree of stenosis was quantified into 5 levels: normal (0%), mild (1%–49%), moderate (50%–70%), severe (71%–90%), critical (91%–100%). Stenosis was considered to be clinically important when the degree of stenosis exceeded 50%.

2.6. Effective dose

The $CTDI_{vol}$ (mGy) and dose length product (DLP) per examination were recorded. The effective dose (ED) of CCTA was calculated as the DLP times a conversion coefficient for the chest ($k = 0.014\ mSv \times (mGy \times cm)^{-1}$).

2.7. Statistical analysis

Analyses were performed using the SPSS software (version 26.0; SPSS, Chicago, Ill). Numerical data were expressed as the mean ±

SD. Mann-Whitney test was used for comparison, and a value of $p < 0.05$ was considered significant. Receiver operator curve (ROC) was used to analyze the factors affecting the number of coronary CTA scans. Sensitivity, specificity, negative predictive values (NPV), positive predictive values (PPV) and accuracy of CCTA were calculated compared to ICA. Intra- and inter-observer agreements for CCTA images quality evaluation were tested with Cohen's Kappa.

3. Results

3.1. Patient characteristics

Patient characteristics were shown in Table 1. The minimal, maximal and mean heart rate of patients with irregular rhythm were significantly higher than that of patients with regular rhythm. No significant differences were found in gender, height, weight and BMI ($p > 0.05$).

3.2. Radiation dose evaluation

The scan parameters were shown in Table 2. The number of scans was higher than those in regular rhythm group (1.3 ± 0.7 vs 1.0 ± 0.0, $p < 0.01$). There were no significantly different in effective dose between regular rhythm and irregular rhythm group (2.7 ± 0.7 vs 2.9 ± 1.3, $p > 0.05$).

The effective dose for patients with regular and irregular rhythm were shown in Fig. 3. Patients with irregular rhythm were divided into three groups according to the number of scans. No significant difference was observed in effective dose between regular rhythm group and irregular rhythm group with 1 scan (2.7 ± 0.7 mSv vs 2.5 ± 0.6 mSv, $p > 0.05$). The effective dose in irregular rhythm groups with 2 scans and more than 2 scans were significantly higher than those in regular rhythm group (4.0 ± 1.7 mSv vs 2.7 ± 0.7 mSv, $p < 0.01$; 5.2 ± 1.9 mSv vs 2.7 ± 0.6 mSv, $p < 0.01$ respectively).

3.3. Effect factors analysis for the number of scans

ROC of different factors effecting the number of scans in irregular rhythm group were shown in Table 3 and Fig. 4. For patients with irregular rhythm, gender was the most important factor affecting the number of scans, and the area under the curve (AUC) was 0.78($p < 0.01$). In the irregular heart rhythm group, 53 patients (34 men and 19 women) received 1 scan in one CCTA examination, 12 patients (3 men and 9 women) received 2 scans, and 5 (0 men and 5 women) patients received 3 or more scans. There were no significant differences in age, BMI, mean and minimal heart rate, and the types of irregular rhythm (all $p > 0.05$) for patients with different number of scans. The number of scans of female patients was significantly higher than that of male patients (1.6 ± 0.8 vs 1.1 ± 0.3, $p < 0.01$).

3.4. Image quality evaluation and diagnostic accuracy of CCTA

The image quality scores of regular rhythm and irregular group were shown in Fig. 5. The mean image quality was similar between the regular rhythm and irregular group (4.34 ± 0.47 vs 4.37 ± 0.48, $p > 0.05$). The kappa values for inter-observer agreement were 0.76 and 0.66, for intra-observer agreement were 0.70 and 0.50.

The diagnostic performance of CCTA in the detection of significant stenosis (>50%) compared with the results of ICA was shown in Table 4. The sensitivity, specificity, NPV, PPV and accuracy were 92.31%, 88.89%, 92.31%, 88.89%, 90.91% in a patient-based analysis, 94.44%, 97.72%, 94.44%, 97.72%, 96.97% in a vessel-based analysis, and 88.46%, 99.39%, 92.00%, 99.10%, 98.61% in a segment-based analysis. Fig. 6 shows the coronary CT angiography and ICA of a patient with irregular heart rhythm.

4. Discussion

In our study, we evaluated the radiation dose, image quality and diagnosis performance of CCTA between regular and irregular rhythm groups using a scanner with an ECG monitoring system and motion correction algorithm. No significant differences in radiation dose and image quality were found in regular and irregular rhythm groups. Specifically, women were found to have a higher incidence of arrhythmia, and the scan times of women were higher than man in irregular rhythm group. Good image quality was

Table 2
Scan parameters.

Parameters	Regular rhythm	Irregular rhythm	*p* value
Scan time(s)	0.8 ± 0.2	1.2 ± 0.8	$p = 0.33$
Number of scans	1.0 ± 0.0	1.3 ± 0.7	$p < 0.01$
DLP(mGy*cm)	190.7.6 ± 47.5	209.2 ± 93.1	$p = 0.64$
Effective dose(mSv)	2.7 ± 0.7	2.9 ± 1.3	$p = 0.61$

Data are expressed either as number (n) or as mean ±standard deviations.
DLP: dose length product.

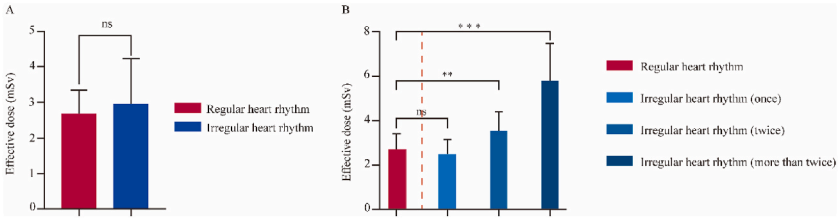

Fig. 3. (A) The effective dose for patients with regular and irregular rhythm. (B) Patients with irregular rhythm were divided into three groups according to the number of scans. **and*** means statistically significant, and ns means statistically not significant.

Table 3
The ROC analysis of different factors effecting the number of scans.

Factors	AUC	95% Confidence interval	*p* value
Age	0.606	0.448–0.763	0.203
Gender	0.727	0.590–0.864	0.006
BMI	0.465	0.304–0.625	0.670
Heart rate			
Mean	0.607	0.437–0.778	0.196
Minimal	0.512	0.316–0.708	0.887
Maximal	0.677	0.518–0.836	0.033
Variation	0.618	0.450–0.786	0.155
The types of arrhythmia	0.368	0.207–0.529	0.111

AUC: area under the curve.

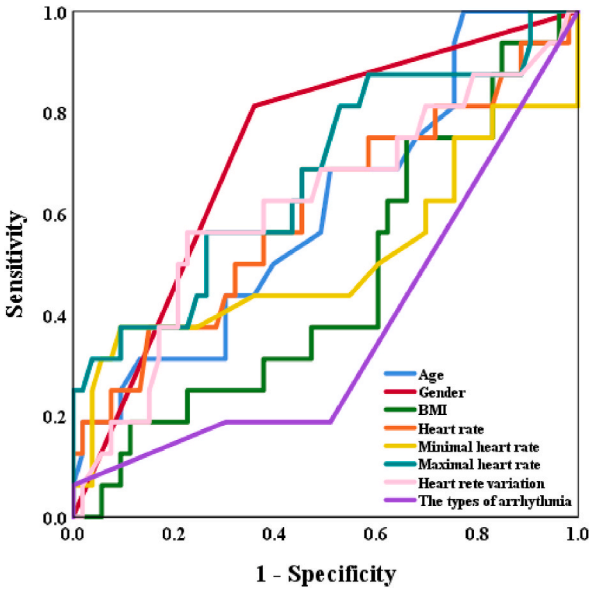

Fig. 4. The ROC of age, gender, BMI, heart rate, heart rate variation and types of arrhythmia in irregular rhythm group depending on the number of scans in one CCTA examination.

observed both in regular and irregular heart rhythm groups. The diagnostic performance of CCTA images in arrhythmia group is consistent with the results of DSA.

The effective radiation dose received by patients in CCTA has always been a hot spot for researchers. Some previous studies showed that radiation exposure was significantly higher in patients with irregular rhythm compared to those with regular rhythm [14,15]. Another study focused on diagnostic accuracy of CCTA using a 16-cm CT reported that the doses of prospectively ECG triggering CCTA were 3.9 mSv for the AF patients and 1.3 mSv for the sinus rhythm patients [16]. In our study, there was not significant differences in radiation dose between patients with regular and irregular rhythm (2.7 mSv vs 2.9 mSv, $p > 0.05$).

The ECG monitoring system could stop scanning immediately, and then start the next scan within the shortest time allowed by the system conditions once detecting the occurrence of arrhythmia. The patients in our study were divided into three groups according to

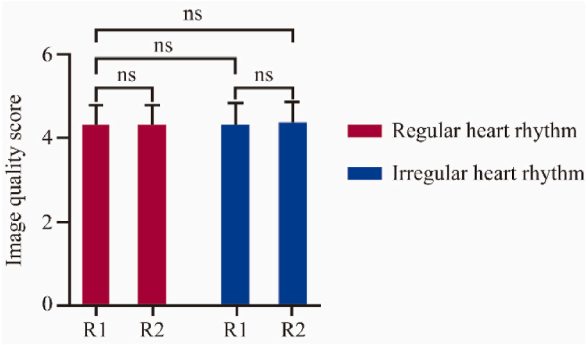

Fig. 5. Image quality evaluated by two radiologists of regular rhythm and irregular group. ns means statistically not significant. R1 and R2 mean radiologist one and two.

Table 4
Comparison of the diagnostic performance of CCTA in significant stenosis (>50%).

Group	Irregular heart rhythm		
Analysis	Patient-based	Vessel-based	Segment-based
Sensitivity	92.31%	94.44%	88.46%
Specificity	88.89%	97.72%	99.39%
NPV	92.31%	94.44%	92.00%
PPV	88.89%	97.72%	99.10%
Accuracy	90.91%	96.97%	98.61%

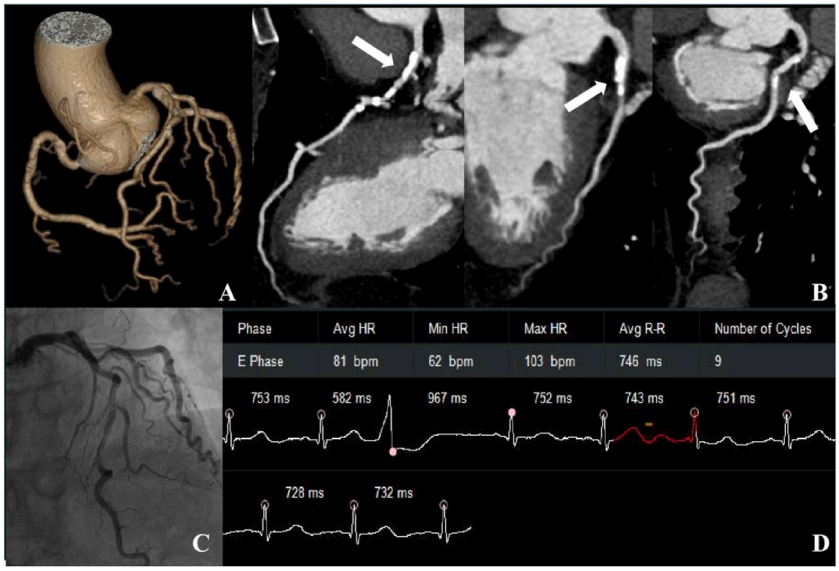

Fig. 6. Images in 70-year-old male patient with coronary artery stenosis. *A*, Coronary artery tree. Coronary CT angiography images (B)and invasive coronary angiography image (C) show 40% stenosis in the middle of the left anterior descending coronary artery with calcification, 90% of the second diagonal coronary artery stenosis with calcification, and 40% stenosis of left circumflex coronary artery. *D*, The electrocardiogram shows that the patient has arrhythmia.

the number of scans in one examination: once, twice and more than twice. The radiation exposure in once group was not significantly different with that in regular heart rhythm group ($p > 0.05$). Inversely, there were significant differences in radiation doses of twice and more than twice group compared to that of regular heart rhythm group ($p < 0.01$).

In our study, the frequency of abnormal heart rhythm fluctuations and the number of scans in female patients was significantly higher than that in male patients during the scan. The difference of gender on heart disease may account for this result [17,18]. Females have a higher incidence of atrioventricular nodal reentry tachycardia, inappropriate sinus tachycardia, supraventricular tachycardia, and sudden cardiac death than males [19].

The image quality between regular and irregular heart rhythm group were similar. The diagnostic performance of coronary CT angiography in irregular heart rhythm group was good. The diagnostic accuracy were 90.91% in patient-based analysis, 96.97% in vessel-based analysis, and 98.61% in segment-based analysis, respectively. The price of high accuracy was the relatively high effective radiation dose. However, the mean effective dose in irregular heart rhythm group (2.9 mSv) in our study was still lower than those reported in previous study [20–22].

There are several limitations in our study. First, the number of patients in irregular heart rhythm was not consistent with that of regular heart rhythm, and only twenty-two patients in irregular heart rhythm who underwent ICA were collected. Second, our study is a single-center study, and our results may not reflect the situation of patients from other regions in our country. Therefore, multi-center research is necessary in future research. Finally, the types of irregular heart rhythm and the small number of patients included in each type may have a potential impact on our results. Thus, further investigation including more types and patients are necessary to validate our results.

5. Conclusion

For patients with irregular heart rhythm, a CT scanner with an ECG monitoring system and motion correction algorithm can not only reduce the radiation dose to the same level as patients with normal heart rhythms, but also ensure that the images with high diagnostic accuracy.

Ethics statement

I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by Heliyon. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated (including images) to support conclusions. No data, text, or theories by others are presented as if they were our own.

The submission has been received explicitly from all co-authors. And authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Zeng,M. , upon reasonable request.

CRediT authorship contribution statement

Cheng Yan: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Data curation. **Jing Liu:** Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ji Min:** Visualization, Validation, Supervision, Software, Project administration. **Heng Zhou:** Validation, Supervision, Project administration. **Junying Gu:** Validation, Supervision, Project administration. **Guofeng Zhou:** Visualization, Validation, Project administration. **Caizhong Chen:** Visualization, Validation, Funding acquisition. **Chun Yang:** Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition. **Mengsu Zeng:** Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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