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Personalized contrast agent dosing to prevent contrast induced nephropathy in high risk populations in Guangdong, China

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Contrast-induced nephropathy (CIN) is an acute kidney injury manifests within 72 h post-administration of contrast media, excluding other kidney-damage etiologies. Despite the recognition of CIN, the complex interplay among high-risk factors remains poorly understood, and precision in the existing risk stratification models is lacking. This retrospective, observational cohort study included patients who underwent percutaneous coronary intervention (PCI) or computed tomography angiography (CTA) at four hospitals in Guangdong, China, between 2010 and 2018. Demographic and clinical characteristics of the patients of prognostic interest were collected. The main outcome was CIN occurrence. In total 12,376 patients were included in the final data analysis. Contrast media dosage was positively associated with CIN risk, with an adjusted odds ratio (OR) of 1.007 for each standard deviation increase in dosage. Doses above 140 ml significantly increased CIN risk (adjusted OR = 3.27). Notably, hypertensive and diabetic patients experienced greater risks at doses > 140 ml. Subgroup analyses underscored the importance of personalized dosage management. This study highlights the critical need for dosage management to mitigate CIN risk, particularly in high-risk patients. Individualized risk assessment and dose optimization strategies are essential to minimize the risk of CIN development and improve patient outcomes.

Keywords Contrast-induced nephropathy, Personalized contrast agent dosing, High-risk populations

Iodinated contrast media are vital in modern medicine, enhancing diagnostic and interventional procedures across various specialties, such as cardiology and neurology. These agents improve image contrast on X-rays, CT scans, and angiography, enabling precise visualization of internal structures. This clarity is crucial for accurately diagnosing and managing diseases, leading to better patient outcomes. Iodinated contrast media enhance diagnostic accuracy and facilitate targeted treatments, underscoring their indispensable value in healthcare[1,2].

Contrast-induced nephropathy (CIN) is a potential complication that can arise following the intravascular administration of contrast media. Since the introduction of iodinated contrast agents in the early 1950s, their ability to delineate vascular structures and improve imaging precision has significantly increased diagnostic accuracy[3,4]. However, soon after their inception, the nephrotoxic potential of these agents was recognized. Over the past few decades, with the increasing use of contrast agents in various procedures, the incidence and implications of CIN have become significant concerns for clinicians[5–7].

CIN incidence rates vary widely, with reporteds values ranging from as low as 2% to as high as 25% in high-risk populations[8–11]. Several risk factors that increase the susceptibility of an individual to CIN developmenthave been identified. These risk factors include preexisting chronic kidney disease (CKD), diabetes mellitus (DM), advanced age, volume depletion, concurrent use of nephrotoxic drugs, and high volumes or repeated doses of contrast media[12–16]. Current evidence incompletely details the intricate interplay of these factors and makes current risk stratification models imprecise. This study addresses these knowledge gaps by exploring nuanced risk factor interactions, refining prediction models, and investigating targeted interventions. Through the

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present findings, we aimed to contribute to the development of more accurate risk assessments and effective clinical strategies, that would advance the prevention and management of CIN.

Therefore, the purpose of this study was to elucidate the relationship between contrast agent dosage and the risk of CIN development, with a particular focus on various patient subgroups differentiated by medical conditions such as DM, hyperuricemia (HUA), heart failure (HF), CKD, and anemia. Our research revealed notable differences in the correlation between contrast agent dosage and CIN risk across various patient subgroups. Specifically, we examined the increased risk of CIN development in patients stratified by sex, age, BMI, DM status, hypertension status, HF status, CKD status, anemia status, and HUA status. Understanding these relationships will be crucial for optimizing contrast agent dosage and minimizing the risk of CIN development in diverse patient populations. Using a threshold effect model, our study further delineated the cutoff points for contrast agent dosage that correspond to an increased risk of CIN development in different patient subgroups. These findings offer valuable insights for clinicians in determining safe contrast agent dosages, particularly in high-risk populations.

Methods

Study design and participants

We conducted a retrospective analysis involving patients who underwent percutaneous coronary intervention (PCI) or computed tomography angiography (CTA) at four hospitals in Guangdong, China, between 2010 and 2018. These hospitals included Dongguan People's Hospital(Tenth Affiliated Hospital of Southern Medical University), Taishan People's Hospital, Dongguan Xiegang People's Hospital, and Guangdong Provincial People's Hospital. This study included patients aged 18 years and above who received either hypo-osmolar nonionic monomeric iodixanol or isotonic nonionic dimer iodixanol contrast agents(both of which contained 320 mgI/ml iodine), and signed an informed consent form.

Exclusion criteria: Patients were excluded if they met the following criteria:

1. Receipt of contrast agents other than those specified;
2. An active tumor status or current treatment with nephrotoxic chemotherapy;
3. No pre- or post-exposure renal function data available within three days of contrast agent administration;
4. Undocumented contrast agent doses;
5. Additional potential confounding factors affecting renal function, including previous acute renal injury, renal insufficiency, renal tubular injury, and other renal diseases, such as diabetes nephropathy, hypertensive nephropathy, or tubulointerstitial diseases.

Data collection

The collected data included demographic details (age, sex, weight, height, blood pressure) and medical history (DM, hypertension, hypotension, HF, CKD, anemia, intra-aortic balloon pump [IABP] use, hydration status). The laboratory parameters included hemoglobin (HGB), renal function (assessed before and within three days postcontrast exposure), and uric acid (UA) levels. Body mass index (BMI) was calculated via the standard formula (weight in kilograms divided by the square of height in meters). The estimated glomerular filtration rate (eGFR) was derived via the CKD Epidemiology Collaboration (CKD-EPI) Equation[17].

Definition of CIN

CIN was defined as an absolute increase in serum creatinine (SCr) of ≥ 0.5 mg/dl (44.2 μmol/L) or a relative increase of ≥ 25% from baseline within 48 to 72 h following contrast exposure.

Covariates

The following covariates were included in the analyses: sex, age, BMI, systolic and diastolic blood pressure, laboratory results (HGB and UA), and disease history (DM, hypertension, hypotension, HF, CKD, anemia, IABP use, hydration status).

Statistical analysis

Continuous variables are presented herein as means ± standard deviations, whereas categorical variables are expressed as percentages. To compare population characteristics according to the occurrence of CIN, one-way analysis of variance (ANOVA) and chi-square tests were used. The association between contrast agent dose and CIN risk was evaluated via multivariate logistic regression, which yielded odds ratios (ORs) and 95% confidence intervals (CIs) adjusted for relevant covariates. The contrast dose was analyzed as both a continuous variable and a categorical variable on the basis of clinically established cutoff points. A penalized spline method was used for smooth curve fitting to visualize the relationship between the contrast agent dose and the risk of CIN development.

Subgroup analyses were conducted to explore potential modifiers affecting the contrast dose–CIN relationship, focusing on variables such as sex, age (divided into < 65 and ≥ 65 years), BMI (divided into < 24 and ≥ 24 kg/m^2), hypertension, DM, HF, CKD, anemia, and high UA levels. Stratified analyses and interaction tests were performed to assess potential effect modifications.

We employed a threshold effect model to capture the nonlinear relationship between the explanatory variable (X) and the outcome variable (Y). In biomedical research, many factors and their associated outcomes do not follow a simple linear relationship. Instead, their effect may be either null or positive within a certain range, and once a threshold is exceeded, the magnitude or direction of the effect may change. To detect such threshold effects, we first applied a smoothing curve fitting technique to examine the relationship between X and Y. This method allowed us to visually assess whether a piecewise linear relationship exists.

To formally identify and validate the threshold, we used the Empower Solutions software by X&Y, which includes a dedicated module for threshold effect analysis. This software utilizes maximum likelihood estimation (MLE) to determine the threshold(s) based on the observed piecewise linear relationship. The software offers two options: if prior knowledge of the threshold exists, the user can input a specified value, or alternatively, the software can automatically determine the threshold based on the data and the segmented fitting approach. In our analysis, we chose to use the software's automatic threshold identification feature.

A two-sided p value of less than 0.05 was considered to indicate statistical significance. All analyses were conducted via R software, version 3.4.3 (www.R-project.org), and EmpowerStats, version 2.17.8 (www.empowerstats.com, X&Y Solutions, Inc.).

Results

Baseline characteristics of the study participants

During the study period, data were collected from 16,038 patients. Among these patients, 227 were excluded because of the absence of renal function data before contrast media administration, 3,371 were excluded because of the absence of pre- and post-exposure renal function data within three days before and after the use of contrast agents, and 64 were excluded because the contrast agent dose was not recorded. This process resulted in a final cohort of 12,376 patients (Fig. 1), with an average age of 63.0 years (standard deviation of 12.4 years), 63.8% of whom were male. The incidence of CIN was 6.4%, affecting 797 of the 12,376 patients included in the analysis (Table 1).

The results of this study revealed that patients who developed CIN were generally characterized by a greater use of contrast, older age, and male sex, along with a lower BMI and HGB concentration. They also had higher systolic and diastolic blood pressure (SBP and DBP), baseline serum creatinine (SCr), blood urea nitrogen (BUN), and uric acid (UA) levels. Hypertension, DM, HF, the use of an intra-aortic balloon pump (IABP), anemia, hydration, and elevated UA were more common in the CIN group ($p < 0.05$). Compared with those who underwent CTA, patients who underwent PCI had a greater probability of CIN development. No significant differences were noted regarding hypotension status (Table 1).

Associations between contrast dosage and CIN incidence

To investigate the impact of contrast agent dosage on the CIN incidence, we initiated a structured analysis focused on understanding the relationship between varying dosages and the incidence of CIN. By employing statistical models and adjusting for confounding variables, we aimed to reveal how different dosages influence CIN risk.

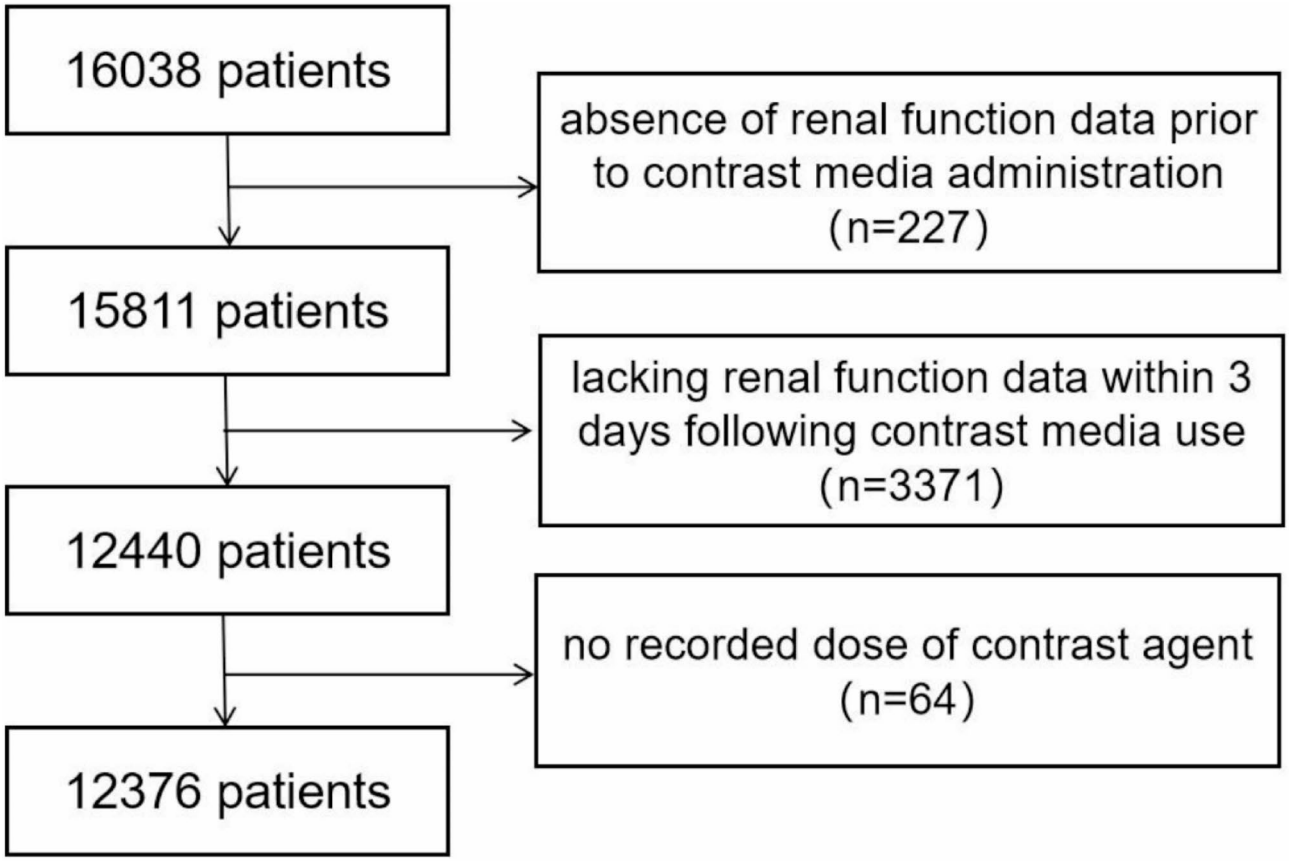

Fig. 1. Flowchart of the study patients.

Characteristics	Total	CIN	No CIN	*p*
N	12,376	797(6.4%)	11,579(93,6%)	
Age, years	63.0 ± 12.4	66.3 ± 12.6	62.8 ± 12.4	<0.001
Male, n (%)	7896 (63.8%)	551 (69.2%)	7345 (63.4%)	0.001
Weight, kg	67.3 ± 13.1	65.1 ± 11.7	67.4 ± 13.2	< 0.001
Height, cm	163.6 ± 9.3	162.4 ± 8.0	163.7 ± 9.3	< 0.001
BMI, kg/m^2	25.1 ± 4.5	24.6 ± 3.7	25.2 ± 4.5	0.001
SBP, mmHg	132.0 ± 23.0	143.6 ± 22.1	131.2 ± 22.8	< 0.001
DBP, mmHg	79.0 ± 12.6	82.3 ± 13.6	78.8 ± 12.5	< 0.001
Hypertension, n (%)	7243 (58.5%)	567 (71.2%)	6676 (57.7%)	< 0.001
Hypotension, n (%)	106 (0.9%)	9 (1.1%)	97 (0.8%)	0.4
SCr, μmol/L	91.7 ± 83.8	192.9 ± 245.9	84.7 ± 51.0	< 0.001
BUN, mmol/L	5.6 ± 3.2	8.80 ± 7.29	5.40 ± 2.60	< 0.001
CKD, n (%)	3675 (29.7%)	437 (54.9%)	3238 (28.0%)	< 0.001
Hydration, n (%)	75 (0.6%)	11 (1.4%)	64 (0.6%)	0.004
DM, n (%)	3382 (27.3%)	282 (35.4%)	3100 (26.8%)	< 0.001
HF, n (%)	1023 (8.3%)	165 (20.7%)	858 (7.4%)	< 0.001
IABP, n (%)	21 (0.17%)	6 (0.8%)	15 (0.1%)	< 0.001
HGB, g/L	130.9 ± 19.4	122.8 ± 23.4	131.4 ± 18.9	< 0.001
Anemia	1887 (15.3%)	259 (32.5%)	1628 (14.1%)	< 0.001
UA, μmol/L	380.4 ± 115.0	405.3 ± 134.8	378.6 ± 113.3	< 0.001
HUA	4362 (35.3%)	350 (44.0%)	4012 (34.6%)	< 0.001
Contrast dosage, ml	115.7 ± 70.6	144.0 ± 88.8	113.8 ± 68.7	< 0.001
Examinations				< 0.001
PCI	5448(44.0%)	419(52.6%)	5029(43.4%)	
CTA	6927(56.0%)	377(47.4%)	6550(56.6%)	

Table 1. Characteristics of the study participants by whether CIN occurred. Note: Data are expressed as the means ± SDs and numbers (percentages) as appropriate. Abbreviations: BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; SCr, serum creatinine; BUN, blood urea nitrogen; CKD, chronic kidney disease; DM, diabetes mellitus; HF, heart failure; IABP, intra-aortic balloon pump; HGB, hemoglobin; HUA, hyperuricemia; PCI, percutaneous coronary intervention; CTA, computed tomography angiography.

The correlation between the dosage of contrast agent and the incidence of CIN is illustrated in Fig. 2, highlighting a discernible increase in the CIN incidence rate in patients with increased contrast agent dosages. A more detailed examination, as summarized in Table 2, confirmed the significant association between incremental increases in contrast agent dosage (per standard deviation) and the incidence of CIN (adjusted odds ratio (OR) 1.007 (95% CI: 1.006–1.008)).

Expanding on these findings, we analyzed outcomes across specific dosage ranges. The multivariate-adjusted ORs for groups receiving 101–110 ml, 111–120 ml, 121–130 ml, and 131–140 ml of contrast agent were 1.09 (0.62, 1.89), 0.90 (0.54, 1.51), 1.65 (0.98, 2.79), and 2.31 (1.24, 4.30), respectively, in comparison to those administered less than 100 ml. Notably, the risk of CIN development increased substantially at higher doses. Compared with doses below 100 ml, doses in the 141–200 ml range were associated with adjusted ORs ranging from 2.29 to 3.66; doses in the 201–300 ml range were associated with an OR of 3.21 (2.46, 4.19); and doses exceeding 300 ml were associated with an OR of 5.78 (4.20, 7.96). This linear trend in the association between contrast agent dosage and CIN incidence was statistically significant (p for trend < 0.001), highlighting the critical need for dosage management in clinical practice to mitigate CIN risk.

In the analysis employing a threshold effect model with a cutoff point of 140 ml, doses of contrast agent above this threshold were associated with a significantly increased risk of CIN development, with an adjusted OR of 3.27 (95% CI: 2.75–3.89). This finding indicates a more than threefold increase in the risk of CIN development associated with dosages exceeding 140 ml.

Subgroup analyses

To further delineate the relationship between contrast agent dosage and the risk of CIN development within specific patient populations, subgroup analyses were performed. These analyses were aimed to determine how underlying health conditions might influence the association between contrast agent dosages and CIN incidence. As illustrated in Fig. 3, the investigation revealed notably stronger associations in patients with preexisting conditions such as hypertension, DM, and HUA when exposed to higher contrast agent doses (greater than 140 ml) than in those who were exposed to lower doses (140 ml or less).

In hypertensive patients, a significant increase in CIN risk was observed, with an odds ratio (OR) of 4.97 (95% CI: 4.01–6.16), which was markedly greater than that in nonhypertensive individuals, who presented an OR of 1.69 (95% CI: 1.26–2.28);this finding highlighted a significant interaction effect (*p*-interaction < 0.001).

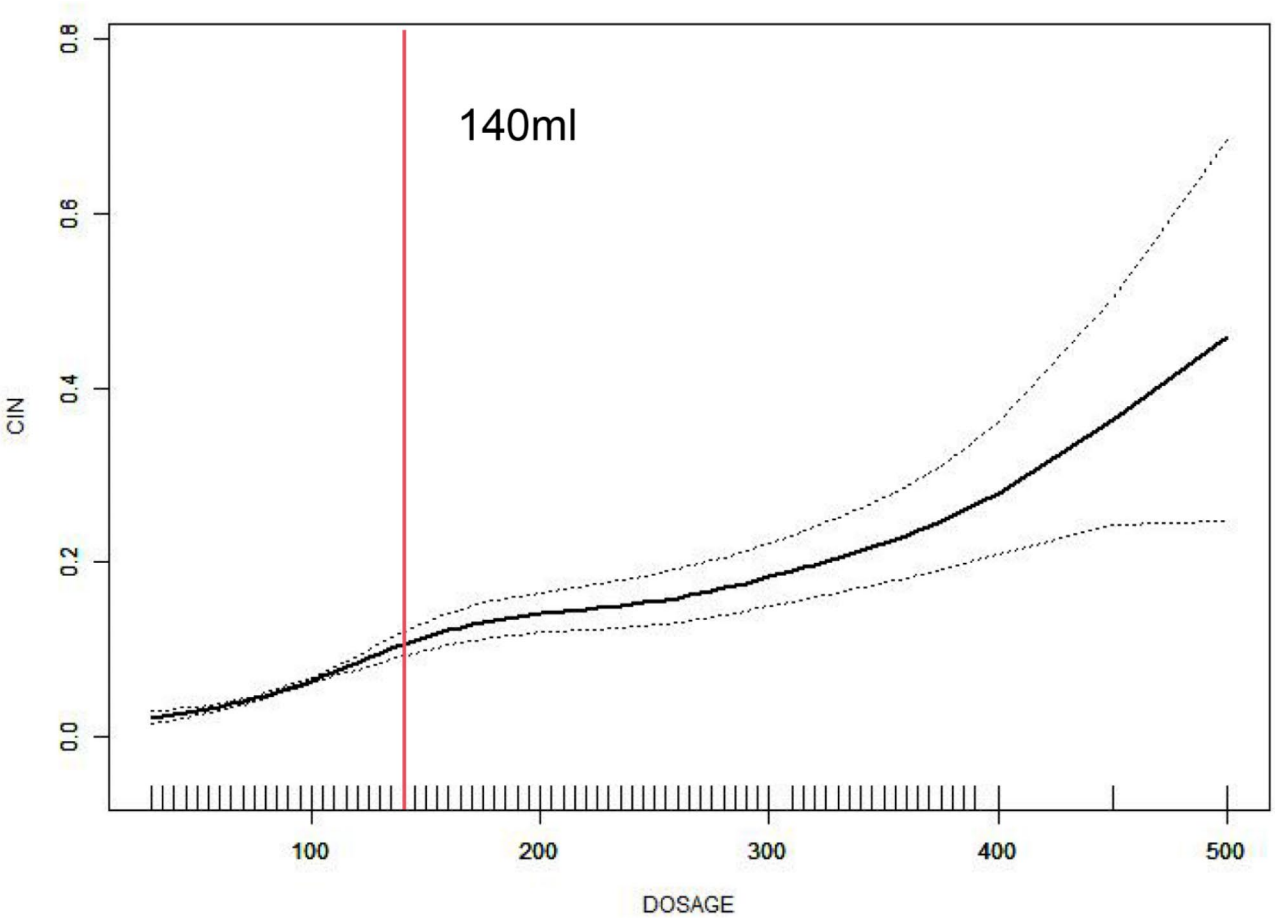

Fig. 2. Threshold effect model of the association between contrast agent dosage and the incidence of CIN. The solid line and dashed line represent the estimated values and their corresponding 95% confidence intervals, respectively. The red vertical line represents the threshold of contrast agent dose. The model was adjusted for age, sex, BMI, SBP, DBP, DM status, HF status, CKD status, IABP use, hydration status, and HGB and UA concentrations.

Similarly, DM patients faced a heightened risk of CIN development (OR = 3.19, 95% CI: 2.58–3.94), albeit slightly lower than that of non-DM patients (OR = 3.36, 95% CI: 2.75–4.09), with a significant interaction effect (p-interaction = 0.02). Moreover, the increase in risk was more pronounced in patients with HUA (OR = 4.43, 95% CI: 3.23–6.07) than in those without HUA (OR = 2.94, 95% CI: 2.38–3.63), which also indicated a significant interaction (p-interaction = 0.002).

There was no significant interaction effect between factors such as sex, age, BMI, HF status, CKD status, and anemia status on the relationship between a contrast agent dose > 140 ml and CIN risk. (all p-interactions > 0.05).

In this investigation, we successfully applied a threshold effect model to identify specific contrast agent dosage levels that mark increased risks for various patient subgroups, directly aligning with the study's objective to understand dosage-related risk variations. Compared with other patients, patients with DM, HF, CKD, anemia or HUA and patients receiving PCI had a greater risk of CIN development at lower dose thresholds (95 ml, 95 ml, 115 ml, 95 ml, 105 ml, and 95 ml, respectively). Compared with non-DM patients, patients without HF, patients with normal renal function, patients without anemia, patients with normal UA levels, and patients receiving CTA had higher tolerance levels (170 ml, 140 ml, 165 ml, 145 ml, 190 ml, and 160 ml, respectively) (Fig. 4).

Discussion

The primary aim of this retrospective study was to investigate the association between contrast agent dosage and the risk of CIN development, with a particular focus on understanding how patient characteristics and procedural factors may modify this relationship. Our analysis of data from 12,376 patients revealed several key findings. The results indicate that as the dosage of the contrast agent increases, the incidence of CIN also significantly increases. Furthermore, this study established a dosage threshold of 140 ml, above which there was a significant increase in the incidence of CIN. This finding underscores the importance of managing contrast agent dosages in clinical practice to mitigate the risk of CIN and reveals a clear linear trend between dosage and CIN incidence that is statistically significant.

Dosage, ml	N	CIN, n (%)	CIN OR (95% CI), p value		
			Crude	Model I	Model II
Per 1-SD increase	12,375	796 (6.43%)	1.005 (1.004, 1.005) < 0.001	1.005 (1.004, 1.006) < 0.001	1.007 (1.006, 1.008) < 0.001
Categories					
0–100	8993	480 (5.34%)	Ref.	Ref.	Ref.
101–110	262	15 (5.73%)	1.08 (0.63, 1.83) 0.8	1.13 (0.67, 1.93) 0.6	1.09 (0.62, 1.89) 0.8
111–120	283	19 (6.71%)	1.28 (0.79, 2.05) 0.3	1.36 (0.85, 2.20) 0.2	0.90 (0.54, 1.51) 0.7
121–130	300	17 (5.67%)	1.07 (0.65, 1.75) 0.8	1.20 (0.73, 1.98) 0.5	1.65 (0.98, 2.79) 0.06
131–140	182	75 (6.59%)	1.25 (0.69, 2.26) 0.5	1.39 (0.77, 2.53) 0.3	2.31 (1.24, 4.30) 0.009
141–200	1185	111 (9.37%)	1.83 (1.48, 2.27) < 0.001	1.99 (1.60, 2.47) < 0.001	2.89 (2.29, 3.66) < 0.001
201–300	731	84 (11.49%)	2.30 (1.80, 2.94) < 0.001	2.37 (1.85, 3.03) < 0.001	3.21 (2.46, 4.19) < 0.001
>300	439	58 (11.26%)	2.70 (2.02, 3.61) < 0.001	3.06 (2.28, 4.11) < 0.001	5.78 (4.20, 7.96) < 0.001
P for trend			< 0.001	< 0.001	< 0.001
Cutoff					
≤ 140	10,020	543 (5.42%)	Ref.	Ref.	Ref.
>140	2355	253 (10.74%)	2.10 (1.80, 2.46) < 0.001	2.24 (1.91, 2.62) < 0.001	3.27 (2.75, 3.89) < 0.001

Table 2. Association of contrast agent dosage with CIN. Note: Model I was adjusted for age, sex, and BMI; Model II was adjusted for age, sex, BMI, SBP, DBP, DM status, HF status, CKD status, IABP use, hydration status, HGB concentrations, UA concentrations and examination methods. Abbreviations: OR, odds ratio; 95% CI, 95% confidence interval.

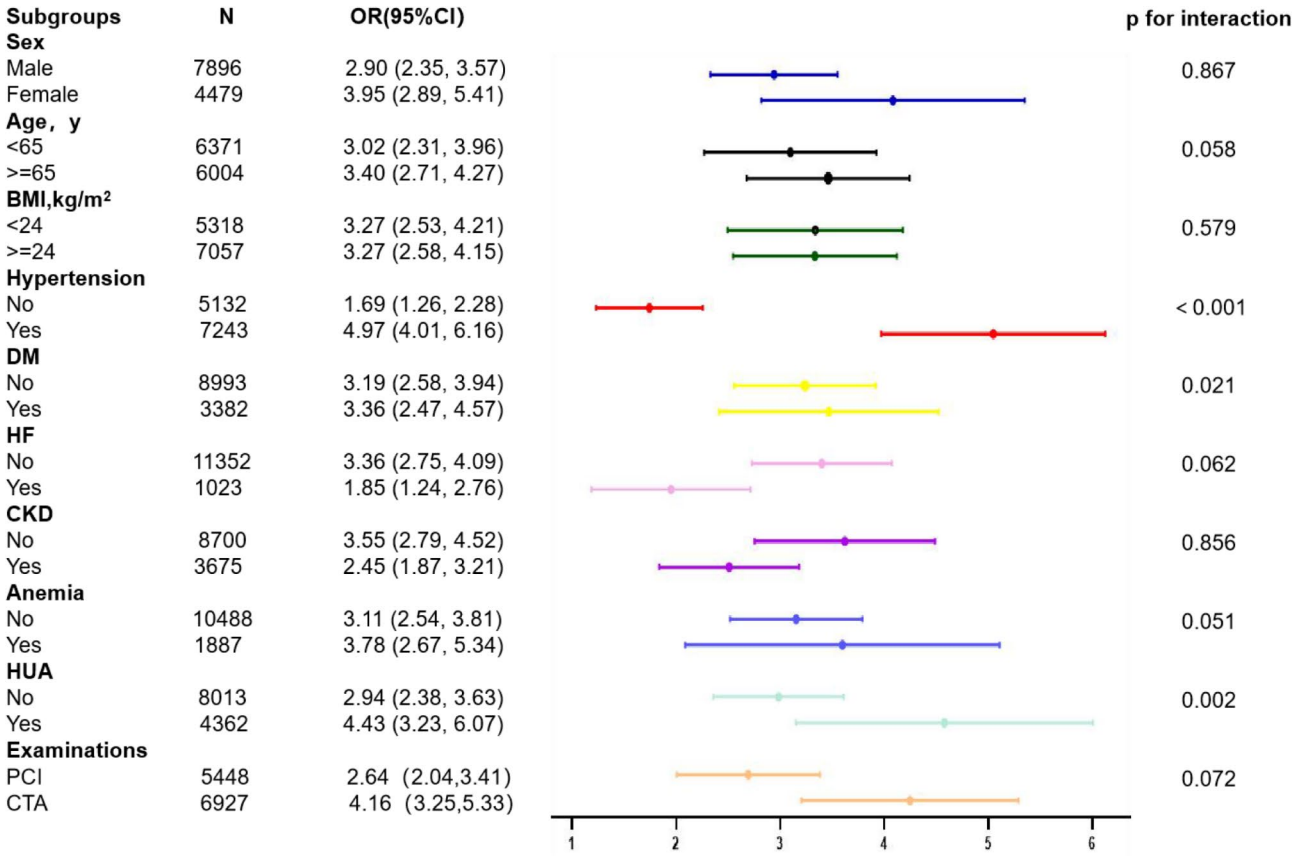

Fig. 3. Associations between contrast agent dosage (≤ 140 ml vs. >140 ml) and the risk of CIN development in various subgroups. Adjusted, if not stratified, for age, sex, BMI, SBP, DBP, DM status, HF status, CKD status, IABP use, hydration status, and HGB and UA concentrations.

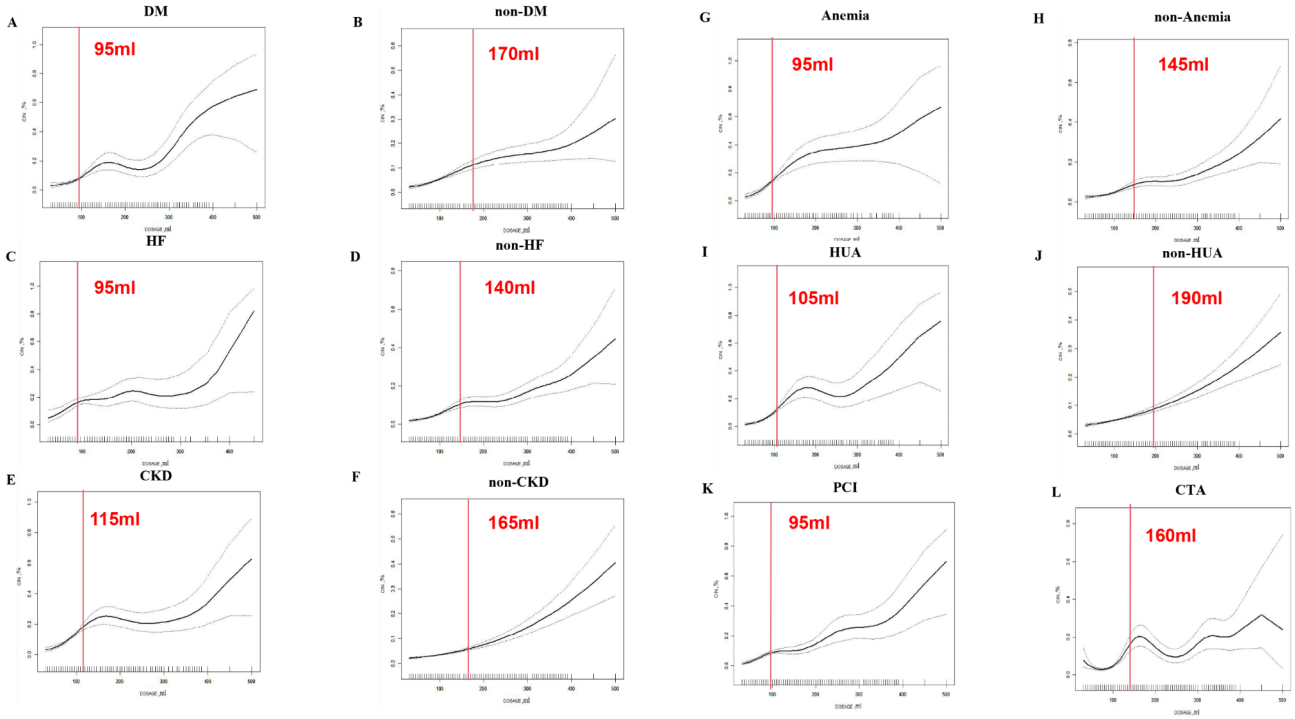

Fig. 4. Threshold effect model of the association between contrast agent dosage and the incidence of CIN in different subgroups. The solid line and dashed line represent the estimated values and their corresponding 95% confidence intervals, respectively. The red vertical line represents the threshold of contrast agent dose. **AB.** The association between contrast agent dose and the risk of CIN development in patients with or without DM. **CD.** The association between contrast agent dose and the risk of CIN development in patients with or without HF. **EF.** The association between contrast agent dose and the risk of CIN development in patients with or without CKD. **GH.** The association between contrast agent dose and the risk of CIN development in patients with or without anemia. **IJ.** The association between contrast agent dose and the risk of CIN development in patients with or without HUA. **KL.** The association between contrast agent dosage and the risk of CIN in patients undergoing PCI or CTA. Adjusted, if not stratified, for age, sex, BMI, SBP, DBP, DM status, HF status, CKD status, IABP use, hydration status, and HGB and UA concentrations.

Subgroup analyses revealed that patients with hypertension, DM, or HUA face significantly greater risks of CIN when exposed to contrast agent dosages above 140 ml. These subgroups exhibited distinct thresholds: patients with DM, HF, CKD, anemia, or HUA are particularly sensitive to lower dosages of contrast agents, with thresholds set at 95 ml, 95 ml, 115 ml, 95 ml, and 105 ml, respectively, during PCI or CTA. Conversely, individuals without these conditions had higher tolerance thresholds, suggesting a differential susceptibility to CIN on the basis of preexisting health conditions.

The findings of this study highlight the complex interplay between contrast agent dosage and the risk of CIN development, particularly in patients with preexisting conditions such as DM and HUA. The observed higher ORs in DM and HUA patients suggest a heightened vulnerability in these subgroups andunderscore the need for careful consideration of contrast agent dosages in these populations.

Delving further into the particular risks associated with DM, the correlation between DM status and a higher risk of CIN development was more pronounced. The increased risk of CIN development (OR: 3.19) in DM patients compared with non-DM patients (OR: 3.36), with a significant p-interaction, indicates that DM may exacerbate the nephrotoxic effects of contrast agents. This finding is consistent with the literature that recognizes DM as a risk factor for renal impairment because of its contribution to vascular and microvascular complications[18,19]. These results call for more stringent monitoring and perhaps a reevaluation of contrast agent dosage thresholds in DM patients undergoing procedures requiring contrast media.

Similarly, the strong correlation between higher contrast agent doses and increased CIN risk in patients with HUA (OR: 4.43), as opposed to those without HUA (OR: 2.94), signals an increased risk in this group. HUA, which is often associated with renal pathology, may act as a synergistic factor exacerbating the nephrotoxicity of contrast agents[20–22]. This novel insight suggests that HUA should be considered a significant risk factor in the management of patients requiring contrast-enhanced imaging procedures.

This differential tolerance reflects the heightened vulnerability of certain populations to CIN, as corroborated by studies indicating that conditions such as DM, HF, CKD, and anemia can significantly impair renal function, thereby increasing the risk of nephrotoxicity from contrast agents[19,23–25].

Although PCI procedures typically require larger volumes of contrast agents for effective vascular imaging and catheter manipulation, especially in complex cases, it is noteworthy that patients undergoing PCI are susceptible

to CIN at relatively lower contrast agent doses than those typically used in CTA. This increased susceptibility in PCI patients can be attributed to factors such as direct exposure of the renal circulation to contrast media and a higher prevalence of preexisting renal impairment among these patients. Second, PCI patients may require multiple administrations of contrast agents postsurgery, particularly after complex procedures or for monitoring postoperative complications. Despite the lower individual doses used each time, cumulative exposure to contrast agents over multiple procedures may also increase the long-term risk of CIN development.

In summary, compared with CTA patients, PCI patients are more prone to CIN development at lower doses because of the higher contrast agent volumes used during procedures, the presence of underlying medical conditions, and potential multiple exposures to contrast agents. These factors highlight the importance of implementing renal protective strategies in clinical practice for PCI patients to mitigate the occurrence of CIN.

The clinical relevance of these findings cannot be overstated. By offering a method to personalize contrast agent dosages on the basis of individual risk profiles, our study paves the way for more effective, personalized strategies to prevent CIN. This approach aligns with the growing emphasis on personalized medicine and the need for individualized risk assessment in the administration of contrast agents[14,26]. In essence, the insights garnered from the application of the threshold effect model underscore the importance of tailored medical interventions for enhancing patient safety and outcomes in the context of contrast agent use.

While our study offers valuable insights into the relationship between contrast agent dosage and the risk of CIN development, it is important to acknowledge several limitations. First, the retrospective nature of the study design introduces inherent biases and limitations, such as the potential for selection bias and incomplete data capture. Additionally, the reliance on electronic health records for data extraction may introduce inaccuracies or missing information. Despite these limitations, our large sample size and rigorous statistical analysis help mitigate these concerns to some extent. Another limitation is the reliance on observational data, which precludes establishing causality between contrast agent dosage and CIN risk. While we observed significant associations, further prospective studies, including randomized controlled trials, are warranted to confirm these findings and elucidate the underlying mechanisms involved.

Despite these limitations, our study offers critical insights into the necessity of individualized dosing strategies for contrast agent administration, especially among high-risk populations such as patients with DM, HF, CKD, anemia, and HUA. By recognizing these limitations and their implications for interpretation, we emphasize the importance of reevaluating dosage thresholds and refining risk assessment models. This approach allows us to better contextualize our findings and guide future research efforts to develop more effective preventive measures and tailored dosing protocols that can significantly reduce the risk of CIN in these vulnerable groups.

Conclusion

Our study emphasizes the urgent need for personalized risk assessment and dose optimization in the administration of contrast agents, with a particular focus on patients with DM, HF, CKD, anemia, or HUA. These findings underscore the necessity of reevaluating current dosage thresholds and developing tailored dosing protocols that can effectively minimize the incidence of CIN in these vulnerable populations. Furthermore, our results support the inclusion of HUA as a critical factor in CIN risk assessment models, which have been previously under represented in clinical practice. Moving forward, it is imperative that research continues to refine these dosing protocols and explore comprehensive strategies to effectively mitigate the risk of CIN.

Data availability

Data is provided within the supplementary information files.

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Declarations

Competing interests
The authors declare no competing interests.

Ethics statement
The study was approved by the Ethics Committee of the Dongguan People's Hospital(Tenth Affiliated Hospital of Southern Medical University), Taishan People's Hospital, Dongguan Xiegang People's Hospital, and Guangdong Provincial People's Hospital, and adhered to the principles of the Declaration of Helsinki. Informed consent was obtained from all participants.

Additional information
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