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Utility of the sum of CT-derived fractional flow reserve in three coronary arteries for predicting long-term prognosis in patients with newly diagnosed unstable angina

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Research Article

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Abstract

Objective: To evaluate the utility of the sum of computed tomography-derived fractional flow reserve in three coronary arteries (3v-CT-FFR) for predicting major adverse cardiac and cerebrovascular events (MACCEs) in patients with newly diagnosed unstable angina (UA).

Methods: This retrospective study included 157 consecutive patients who were diagnosed with UA via coronary CT angiography and concurrent invasive coronary angiography between January 2021 and December 2022 at the First Affiliated Hospital of Bengbu Medical University. The 3v-CT-FFR was defined as the sum of the CT-FFR values for the left anterior descending artery, left circumflex artery, and right coronary artery. The primary endpoint was the occurrence of MACCEs, including all-cause death, cardiac death, nonfatal myocardial infarction, recurrent angina, heart failure, unplanned revascularization, and/or stroke. The optimal cutoff value was determined using receiver operating characteristic curve analysis. Kaplan–Meier survival curves and Cox proportional hazards models were constructed to evaluate the independent utility of the 3v-CT-FFR for predicting MACCEs.

Results: A total of 157 patients were included in this study, with a median follow-up duration of 30 months. During follow-up, 43 MACCEs (27.4%) were reported. The optimal 3v-CT-FFR cutoff value for predicting MACCEs was 2.50, with an area under the curve of 0.729 (95% confidence interval [CI]: 0.646–0.812, P <0.001), a sensitivity of 81.4%, and a specificity of 57.0%. Patients with a 3v-CT-FFR ≤ 2.50 had a significantly greater incidence of MACCEs than did those with a 3v-CT-FFR > 2.50 (38.0% *vs.* 16.7%, P = 0.003). Multivariate Cox regression analysis revealed that a 3v-CT-FFR ≤ 2.50 was an independent risk factor for MACCEs (hazard ratio: 4.121; 95% CI: 2.108–8.054; P < 0.001). Kaplan–Meier analysis showed that the event-free survival rate was significantly lower in the 3v-CT-FFR ≤ 2.50 group than in the >2.50 group (log-rank P < 0.001).

Conclusion: A 3v-CT-FFR value ≤ 2.50 is a significant predictor of mid- to long-term MACCEs in patients with newly diagnosed UA. It holds potential value for clinical risk stratification and may help guide interventional decision-making.

INTRODUCTION

Coronary atherosclerotic heart disease (CAHD) is a leading cause of cardiovascular mortality worldwide. Among acute coronary syndromes, unstable angina (UA) is a particular concern given its rapid progression and high short-term risk of cardiovascular events, making it a key focus for acute intervention and long-term management strategies [1, 2]. Accurate and noninvasive identification of high-risk patients with CAHD, followed by individualized treatment, is critical for reducing mortality and hospital readmission rates [3–5].

Traditional coronary angiography (CAG) and coronary computed tomography angiography (CCTA) can clearly delineate the anatomical severity of stenosis. However, both modalities have limitations in assessing functional ischemia, as anatomical findings alone may not accurately reflect hemodynamic

significance. Fractional flow reserve (FFR), an invasive measure based on the ratio of distal to proximal coronary pressure across a stenotic lesion, has been validated as an effective guide for interventional decisions and prognostic improvement when the FFR is ≤ 0.80 and is regarded as the gold standard for evaluating functional stenosis [6–8]. Nevertheless, its clinical application is limited by the use of pressure wires, adenosine administration, and invasive procedures. CT-derived FFR (CT-FFR), which is based on computational fluid dynamics or machine learning algorithms applied to CCTA data, offers a noninvasive option for obtaining three-dimensional hemodynamic information. CT-FFR enables simultaneous anatomical and functional assessment and has shown high diagnostic concordance with invasive FFR [9].

Patients with UA often present with multivessel coronary artery disease (CAD), yet single-vessel CT-FFR reflects only localized functional status and fails to provide a comprehensive assessment of the overall myocardial ischemic burden. Invasive FFR studies have introduced the concept of the “sum of triple vessel FFR” (3v-FFR), which allows for an integrated evaluation of global myocardial perfusion risk. Compared with single-vessel FFR, this metric has demonstrated superior predictive value for mid- to long-term major adverse cardiac and cerebrovascular events (MACCEs) in multicenter cohorts [10]. However, the prognostic significance of a corresponding CT–FFR-based triple vessel index in patients with newly diagnosed UA has yet to be systematically investigated.

This study is the first to use the sum of the CT-FFR values from the left anterior descending artery, left circumflex artery, and right coronary artery—referred to as triple vessel CT-FFR (3v-CT-FFR)—to evaluate its predictive performance for mid- to long-term MACCEs in patients with newly diagnosed UA. The 3v-CT-FFR was compared with conventional clinical and imaging parameters to assess its potential as a quantitative tool for noninvasive risk stratification and therapeutic decision-making. We hypothesize that 3v-CT-FFR reflects the functional burden of the total plaque load and may offer significant value in identifying high-risk patients, thereby supporting early intervention or intensified pharmacological intervention.

MATERIALS AND METHODS

1.1 Study Subjects

This retrospective study included consecutive patients with UA who underwent both CCTA and CAG at the First Affiliated Hospital of Bengbu Medical University between January 2021 and December 2022. The assessment of coronary artery stenosis severity and plaque characteristics via CCTA was based on the 2024 consensus statement by the Asian Society of Cardiovascular Imaging on coronary artery stenosis and plaque evaluation in CCTA, as well as the 2021 expert consensus from the US National Institutes of Health on CCTA [11, 12]. The study protocol was reviewed and approved by the Ethics Committee of Bengbu Medical University (Ethics Approval No. [2023]KY046).

1.1.1 Inclusion Criteria: (1) completion of both CCTA and initial CAG; (2) first-time diagnosis of UA; (3) availability of complete medical history and follow-up data; and (4) follow-up duration ≥ 12 months.

1.1.2 Exclusion Criteria: (1) acute myocardial infarction within the past week; (2) previously diagnosed CAD based on prior CAG; (3) presence of left main CAD or chronic occlusion on CCTA; (4) severe liver or kidney dysfunction, including aspartate aminotransferase or alanine aminotransferase levels higher than three times the upper limit of normal, liver cirrhosis or other significant hepatic diseases, kidney insufficiency with estimated glomerular filtration rate ≤ 60 mL/min/1.73 m^2; (5) acute or decompensated chronic heart failure with New York Heart Association functional class III–IV; (6) other active inflammatory conditions, including acute infections or uncontrolled autoimmune diseases; and (7) incomplete clinical data or poor-quality CCTA images precluding accurate plaque characterization and data analysis.

1.2 Follow-up and Clinical Endpoints

As of September 31, 2024, follow-up data were obtained for all patients through a review of hospital medical records and telephone interviews. The median follow-up duration was 30 months. MACCEs were defined as the occurrence of any of the following: all-cause mortality, cardiac death, myocardial infarction, recurrent angina, in-stent restenosis, in-stent thrombosis, or stroke.

1.3 Instruments and Methods

1.3.1 Blood Tests

On the morning of the day following admission, 5 mL of venous blood was drawn from the cubital vein of each patient into heparinized tubes. The samples were sent to the hospital's central laboratory for analysis of blood glucose, lipid profile, comprehensive metabolic panel, cardiac enzyme panel, cardiac troponin, and N-terminal pro-B-type natriuretic peptide.

1.3.2 CAG

CAG was performed by experienced cardiologists using the Judkins technique. The interpretation of angiographic findings was based on the 2001 guidelines from the American College of Cardiology and American Heart Association for the diagnosis and management of CAD. The severity of coronary artery stenosis in each vessel was quantitatively assessed using the Gensini scoring system. Two experienced cardiologists independently evaluated the angiograms, and the average score was used for analysis.

1.3.3 CT

CCTA was performed using either a 128-slice spiral CT scanner (iCT, Philips) or a 256-slice spiral CT scanner (Revolution CT, GE Healthcare, USA). Retrospective electrocardiogram-gated scanning was employed, covering the region from 1 cm below the carinal bifurcation to 1 cm below the diaphragm. Iodinated contrast medium was injected at a flow rate of 5.3–5.6 mL/s, with a total volume of 50–70 mL.

For iCT scanning, the primary parameters were as follows: tube voltage of 120 kV, tube current of 800 mA, collimator and detector width of 128 mm × 0.625 mm, slice thickness of 0.9 mm, and gantry rotation time of 0.27 s. For Revolution CT, the key parameters were as follows: tube voltage of 120 kV/100 kV, automated tube current modulation, collimator width of 160 mm, and gantry rotation time of 0.28 s. The image slice thickness was set at 0.625 mm. All CCTA datasets were transferred to a postprocessing workstation (ADW 4.7, GE) for analysis. CT-FFR values were calculated using deep learning-based software (DEEPVESSELFFR, Keya Medical, Beijing, China). The software uses a diastolic-phase image of optimal quality to compute CT-FFR values. The core principle involves training a validated model through deep learning that integrates anatomical and hemodynamic features extracted from large-scale vascular data, enabling rapid and accurate computation of the FFR across the entire coronary tree [13]. CT-FFR measurements were taken at 1.5–2 cm proximal and distal to the stenotic lesions. In cases of multiple lesions within a single vessel, the value at the most distal lesion was used [14]. The 3v-CT-FFR was defined as the sum of the CT-FFR values for the left anterior descending artery, left circumflex artery, and right coronary artery.

1.5 Statistical Methods

Statistical analyses were performed using SPSS27, MedCalc version 20.0.4, and GraphPad Prism 9.0. Normally distributed data are expressed as mean ± standard deviation ($\bar{x} \pm s$), and comparisons between two groups were conducted using independent samples t tests. For nonnormally distributed data, values are presented as medians with interquartile ranges (M [P25, P75]), and comparisons were made using the Mann–Whitney U test. Enumeration data are expressed as counts and percentages (*n* [%]), and comparisons between groups were performed using the chi-square (χ^2) test. Pearson correlation analysis was used to evaluate the relationship between the degree of coronary lumen stenosis and the CT-FFR values. Multivariate Cox regression analysis was employed to identify factors associated with the occurrence of MACCEs. Receiver operating characteristic (ROC) curves were constructed to compare the predictive performance of coronary lumen stenosis and CT-FFR for MACCEs. All probability values were two-sided, and a *P* value < 0.05 was considered statistically significant.

RESULTS

2.1 ROC Curve Analysis of the 3v-CT-FFR for Predicting MACCEs

The ROC curve analysis identified 2.5 as the optimal cutoff value for 3v-CT-FFR in predicting MACCEs, yielding a sensitivity of 81.4%, specificity of 57.0%, and an area under the curve (AUC) of 0.727 (95% confidence interval [CI]: 0.644–0.810, $P < 0.001$). On the basis of this cutoff, patients were stratified into a high 3v-CT-FFR group (> 2.5, $n = 75$) and a low 3v-CT-FFR group (≤ 2.5, $n = 78$).

Variable	AUC	95% CI	Sensitivity	Specificity	Optimal cutoff	Youden index
3v-CT-FFR	0.727	0.644–0.810	0.814	0.570	2.5	0.57

2.2 Comparison of Baseline Characteristics Between the Two Group

Among the 157 patients included in this study, 97 (61.8%) were male and 60 (38.2%) were female, with a mean age of 61.71 ± 11.32 years. Compared with those in the 3v-CT-FFR > 2.5 group, patients in the 3v-CT-FFR ≤ 2.5 group ($n = 79$) had significantly higher levels of B-type natriuretic peptide (BNP), a greater proportion of patients who underwent percutaneous coronary intervention (PCI), and more frequent postoperative use of aspirin and ticagrelor (all $P < 0.05$) (Table 1). Among the 79 patients in the 3v-CT-FFR ≤ 2.5 group, 59 underwent PCI. These patients had significantly longer survival than those who received conservative treatment did ($P < 0.05$) (Table 2). Among the 78 patients in the 3v-CT-FFR > 2.5 group, 36 underwent PCI, and they also had significantly longer survival than those receiving conservative treatment did ($P < 0.05$) (Table 3). Among the 62 patients who did not undergo PCI, 20 had a 3v-CT-FFR ≤ 2.5. Although survival time did not differ significantly between the low- and high-3v-CT-FFR subgroups ($P > 0.05$), the incidence of MACCEs was significantly greater in the ≤ 2.5 group ($P < 0.05$) (Table 4). Among the 95 patients who underwent PCI, 59 had a 3v-CT-FFR ≤ 2.5. There were no statistically significant differences in survival time or MACCEs incidence between the ≤ 2.5 and > 2.5 groups in this subgroup ($P > 0.05$) (Table 5).

Patients were further categorized on the basis of the occurrence of MACCEs into the MACCEs group ($n = 43$) and the non-MACCEs group ($n = 114$). Compared with the non-MACCEs group, patients in the MACCEs group had significantly greater proportions of males, individuals with diabetes, and smokers. Additionally, the levels of serum creatinine and BNP were significantly elevated, whereas high-density lipoprotein levels and survival time were significantly lower (all $P < 0.05$). No significant differences were observed between the two groups in terms of age, hypertension status, postoperative aspirin use, or triglyceride levels (all $P > 0.05$) (Table 6).

2.3 Comparison of Coronary Lesions between the MACCEs and Non-MACCEs Groups

Among the 157 patients, 60 (38.2%) had triple-vessel CAD. The median 3v-CT-FFR across the cohort was 2.50 (2.29, 2.64), and the median Gensini score was 32.00 (14.00, 52.75). Compared with the non-MACCEs group, the MACCEs group had a significantly greater proportion of patients with triple vessel disease, lower 3v-CT-FFR values, and higher Gensini scores (all $P < 0.05$) (Table 7).

Table 1
Comparison of baseline characteristics between the two groups

Age (year)	**Total**	**3v-CT-FFR ≤ 2.5 (n = 79)**	**3v-CT-FFR>2.5 (n = 78)**	***P* value**
	61.76 ± 11.30	**61.53 ± 12.26**	**61.99 ± 10.30**	**0.801**
Male (%, n)	97 (61.8%)	51 (64.6%)	46 (59.0%)	0.475
Hypertension (%, n)	91 (58.0%)	49 (62.0%)	42 (53.8%)	0.299
Diabetes (%, n)	40 (25.5%)	17 (21.5%)	23 (29.5%)	0.252
Atrial fibrillation (%, n)	9 (5.7%)	5 (6.3%)	4 (5.1%)	1
Cerebral infarction (%, n)	30 (19.1%)	15 (19.0%)	15 (19.2%)	0.969
Smoking history (%, n)	84 (53.5%)	40 (50.6%)	44 (56.4%)	0.468
Aspirin (%, n)	143 (91.1%)	77 (97.5%)	66 (84.6%)	0.005
Clopidogrel (%, n)	51 (32.5%)	25 (31.6%)	26 (33.3%)	0.821
Ticagrelor (%, n)	77 (49.0%)	48 (60.8%)	29 (37.2%)	0.003
Statins (%, n)	154 (98.1%)	77 (97.5%)	77 (98.7%)	1
ARNI (%, n)	76 (48.4%)	40 (50.6%)	36 (46.2%)	0.574
Survival time(day)	938.00 (692.00, 1198.00)	997.00 (415.00, 1225.00)	932.50 (759.50, 1174.00)	0.733
PCI (%, n)	95 (60.5%)	59 (74.7%)	36 (46.2%)	<0.001
Glucose(mmol/L)	5.35 (4.42, 6.23)	5.28 (4.38, 6.48)	5.30 (4.69, 6.23)	0.104
Uric acid(umol/L)	305.43 ± 84.29	302.79 ± 86.52	308.07 ± 82.48	0.701
Creatinine(umol/L)	68.00 (59.00, 75.00)	67.00 (59.00, 74.00)	67.50 (59.00, 76.75)	0.62
Total cholesterol(mmol/L)	3.95 (3.16, 4.41)	3.67 (3.04, 4.17)	3.95 (3.39, 4.84)	0.579
Triglycerides(mmol/L)	1.42 (0.96, 1.75)	1.32 (1.02, 1.83)	1.37 (0.89, 2.00)	0.968
Low-density lipoprotein(mmol/L)	2.31 (1.72, 2.83)	2.04 (1.57, 2.72)	2.20 (1.77, 2.96)	0.826
High-density lipoprotein(mmol/L)	1.02 (0.86, 1.16)	0.91 (0.82, 1.20)	1.01 (0.85, 1.18)	0.37
Lipoprotein a(mmol/L)	205.00 (104.50, 331.50)	184.00 (88.75, 353.25)	145.50 (76.00, 397.00)	0.963

Age (year)	Total	3v-CT-FFR ≤ 2.5 (n = 79)	3v-CT-FFR>2.5 (n = 78)	*P* value
	61.76 ± 11.30	**61.53 ± 12.26**	**61.99 ± 10.30**	**0.801**
N-terminal pro-B-type-natriuretic peptide(pg/ml)	115.50 (43.70, 241.81)	79.30 (51.30, 172.00)	44.20 (32.15, 127.75)	0.02
Creatine kinase(U/L)	87.50 (53.00, 93.50)	75.50 (49.75, 95.00)	64.00 (44.00, 111.00)	0.398
MACCEs (%, n)	43 (27.4%)	30 (38.0%)	13 (16.7%)	0.003

Table 2
PCI *vs.* non-PCI outcomes in patients with a 3v-CT-FFR ≤ 2.5

Age (year)	**Total**	**3v-CT-FFR ≤ 2.5 + PCI (*n* = 59)**	**3v-CT-FFR ≤ 2.5 + non-PCI (n = 20)**	***P* value**
	61.53 ± 12.26	**61.49 ± 11.39**	**61.65 ± 14.88**	**0.961**
Male (%, n)	51 (64.6%)	36 (61.0%)	15 (75.0%)	0.259
Hypertension (%, n)	49 (62.0%)	39 (66.1%)	10 (50.0%)	0.200
Diabetes (%, n)	17 (21.5%)	13 (22.0%)	4 (20.0%)	>0.999
Atrial fibrillation (%, n)	5 (6.3%)	3 (5.1%)	2 (10.0%)	0.803
Cerebral infarction (%, n)	15 (19.0%)	13 (22.0%)	2 (10.0%)	0.392
Smoking history (%, n)	40 (50.6%)	27 (45.8%)	13 (65.0%)	0.137
Aspirin	77(97.5%)	58(98.3%)	19(95.0%)	0.416
Ticagrelor	48(60.8%)	40(67.8%)	8(40.0%)	0.028
Clopidogrel (%, n)	25 (31.6%)	19 (32.2%)	6 (30.0%)	0.855
Statins (%, n)	77 (97.5%)	57 (96.6%)	20 (100.0%)	>0.999
ARNI (%, n)	40 (50.6%)	30 (50.8%)	10 (50.0%)	0.948
Glucose(mmol/L)	5.28 (4.38, 6.48)	5.42 (4.38, 6.76)	4.67 (4.38, 5.82)	0.656
Uric acid(umol/L)	302.79 ± 86.52	298.86 ± 83.09	315.44 ± 98.27	0.481
Creatinine(umol/L)	67.00 (59.00, 74.00)	69.00 (65.00, 92.00)	67.00 (59.00, 71.00)	0.293
Total cholesterol(mmol/L)	3.67 (3.04, 4.17)	3.68 (3.62, 4.33)	3.60 (3.02, 4.16)	0.332
Triglycerides(mmol/L)	1.32 (1.02, 1.83)	1.48 (0.98, 2.02)	1.30 (1.03, 1.80)	0.856
Low-density lipoprotein(mmol/L)	2.04 (1.57, 2.72)	2.15 (1.83, 2.81)	1.97 (1.54, 2.53)	0.261
High-density lipoprotein(mmol/L)	0.91 (0.82, 1.21)	0.93 (0.84, 1.34)	0.89 (0.81, 1.20)	0.345
Lipoprotein a(mmol/L)	184.00 (88.75, 353.25)	138.00 (53.00, 372.00)	192.00 (100.00, 350.00)	0.681
N-terminal pro-B-type-natriuretic peptide(pg/ml)	79.30 (51.30, 172.00)	131.90 (54.80, 361.00)	75.60 (50.40, 169.00)	0.403

Age (year)	**Total**	**3v-CT-FFR ≤ 2.5 + PCI (*n* = 59)**	**3v-CT-FFR ≤ 2.5 + non-PCI (n = 20)**	***P* value**
	61.53 ± 12.26	**61.49 ± 11.39**	**61.65 ± 14.88**	**0.961**
Creatine kinase(U/L)	75.50 (49.75, 95.00)	90.00 (73.00, 184.00)	65.00 (46.00, 95.00)	0.048
Survival time(day)	997.00(415.00, 1225.00)	1080.50(775.00, 1276.50)	868.00(724.35, 990.00)	0.045
MACCEs	30(38.0%)	21(35.6%)	9(45.0%)	0.454

Table 3
PCI *vs.* non-PCI outcomes in patients with a 3v-CT-FFR > 2.5

Age (year)	**Total**	**3v-CT-FFR > 2.5 + PCI (n = 36)**	**3v-CT-FFR > 2.5 + non-PCI (n = 42)**	***P* value**
	61.99 ± 10.30	**62.00 ± 11.79**	**61.98 ± 8.98**	**0.992**
Male (%, n)	46 (59.0%)	20 (55.6%)	26 (61.9%)	0.570
Hypertension (%, n)	42 (53.8%)	21 (58.3%)	21 (50.0%)	0.462
Diabetes (%, n)	23 (29.5%)	8 (22.2%)	15 (35.7%)	0.193
Atrial fibrillation (%, n)	4 (5.1%)	1 (2.8%)	3 (7.1%)	0.722
Cerebral infarction (%, n)	15 (19.2%)	6 (16.7%)	9 (21.4%)	0.595
Smoking history (%, n)	44 (56.4%)	18 (50.0%)	26 (61.9%)	0.291
Aspirin	66 (84.6%)	36 (100%)	30 (71.4%)	< 0.001
Ticagrelor	29 (37.2%)	22 (61.1%)	7 (16.7%)	< 0.001
Clopidogrel (%, n)	26 (33.3%)	14 (38.9%)	12 (28.6%)	0.335
Statins (%, n)	77 (98.7%)	36 (100.0%)	41 (97.6%)	>0.999
ARNI (%, n)	36 (46.2%)	16 (44.4%)	20 (47.6%)	0.779
Glucose(mmol/L)	5.13 (4.43, 5.83)	5.49 (4.31, 6.06)	5.24 (4.76, 6.47)	0.696
Uric acid(umol/L)	308.07 ± 82.48	298.81 ± 88.06	316.40 ± 77.28	0.610
Creatinine(umol/L)	68.00 (59.00, 76.00)	66.00 (57.50, 82.00)	67.50 (62.50, 74.25)	0.305
Total cholesterol(mmol/L)	3.88 (3.22, 4.79)	3.76 (3.17, 5.31)	3.95 (3.39, 4.60)	0.736
Triglycerides(mmol/L)	1.37 (0.87, 1.82)	1.18 (0.85, 2.25)	1.43 (0.91, 1.89)	0.881
Low-density lipoprotein(mmol/L)	2.20 (1.70, 2.94)	2.36 (1.49, 3.28)	2.05 (1.79, 2.78)	0.49
High-density lipoprotein(mmol/L)	1.01 (0.87, 1.18)	0.95 (0.83, 1.17)	1.08 (0.87, 1.18)	0.337
Lipoprotein a(mmol/L)	172.50 (93.50, 396.00)	282.00 (115.50, 413.00)	110.00 (56.00, 240.50)	0.068
N-terminal pro-B-type-natriuretic peptide(pg/ml)	46.55 (33.20, 133.00)	47.00 (33.00, 153.10)	42.35 (27.78, 97.75)	0.282

Age (year)	Total	3v-CT-FFR > 2.5 + PCI (n = 36)	3v-CT-FFR > 2.5 + non-PCI (n = 42)	*P* value
	61.99 ± 10.30	**62.00 ± 11.79**	**61.98 ± 8.98**	**0.992**
Creatine kinase(U/L)	64.00 (44.00, 111.00)	48.00 (39.00, 67.35)	89.00 (52.25, 118.50)	0.013
Survival time(day)	932.50 (759.50, 1174.00)	1080.50 (775.00, 1276.50)	868.00 (724.35, 990.00)	0.008
MACCEs	13 (16.7%)	7 (19.4%)	6 (14.3%)	0.542

Table 4
Outcomes in non-PCI patients by 3v-CT-FFR value

Age (year)	**Total**	**Non-PCI + 3v-CT-FFR > 2.5 (*n* = 42)**	**Non-PCI + 3v-CT-FFR ≤ 2.5 (*n* = 20)**	***P* value**
	61.87 ± 11.10	**61.98 ± 8.98**	**61.65 ± 14.88**	**0.915**
Male (%, n)	41 (66.1%)	26 (61.9%)	15 (75.0%)	0.308
Hypertension (%, n)	31 (50.0%)	21(50.0%)	10 (50.0%)	>0.999
Diabetes (%, n)	19 (30.6%)	15 (35.7%)	4 (20.0%)	0.210
Atrial fibrillation (%, n)	5 (8.1%)	3 (7.1%)	2 (10.0%)	>0.999
Cerebral infarction (%, n)	11 (17.7%)	9 (21.4%)	2 (10.0%)	0.456
Smoking history (%, n)	39 (62.9%)	26 (61.9%)	13 (65.0%)	0.814
Aspirin (%, n)	49 (79.0%)	30 (71.4%)	19 (95.0%)	0.072
Clopidogrel (%, n)	18 (29.0%)	12 (28.6%)	6 (30.0%)	0.908
Ticagrelor (%, n)	15 (24.2%)	7 (16.7%)	8 (40.0%)	0.901
Statins (%, n)	61 (98.4%)	41 (97.6%)	20 (100.0%)	>0.999
ARNI (%, n)	30 (48.4%)	20 (47.6%)	10 (50.0%)	0.861
Glucose(mmol/L)	5.16(4.63, 6.02)	5.24 (4.76, 6.47)	4.67(4.38, 5.82)	0.585
Uric acid(umol/L)	316.10.±82.46	316.40 ± 77.28	315.44 ± 98.27	0.968
Creatinine(umol/L)	68.00 (64.50, 77.50)	67.50 (62.50, 74.25)	69.00 (65.00, 92.00)	0.827
Total cholesterol(mmol/L)	3.86 (3.43, 4.43)	3.95 (3.39, 4.60)	3. 68(3.62, 4.33)	0.785
Triglycerides(mmol/L)	1.43(0.96, 1.92)	1.43 (0.91, 1.89)	1.48 (0.98, 2.02)	0.925
Low-density lipoprotein(mmol/L)	2.08 (1.82, 2.79)	2.05 (1.79, 2.78)	2.15 (1.83, 2.81)	0.353
High-density lipoprotein(mmol/L)	1.00(0.85, 1.19)	0.94 (0.83, 1.17)	0.89 (0.81, 1.20)	0.971
Lipoprotein a(mmol/L)	206.00 (101.00, 394.00)	110.00 (56.00, 240.50)	138.00 (53.00, 372.00)	0.649
N-terminal pro-B-type-natriuretic peptide(pg/ml)	113.00 (56.00, 268.00)	42.35 (27.78, 97.75)	131.90 (54.80, 361.00)	0.067
Creatine kinase(U/L)	90.00 (58.50, 123.00)	89.00 (52.25, 118.50)	90.00 (73.00, 184.00)	0.355
Survival time(day)	844.50 (679.00,	840.36 ± 244.37	680.90 ± 423.60	0.130

Age (year)	Total	Non-PCI + 3v-CT-FFR > 2.5 (*n* = 42)	Non-PCI + 3v-CT-FFR ≤ 2.5 (*n* = 20)	*P* value
	61.87 ± 11.10	**61.98 ± 8.98**	**61.65 ± 14.88**	**0.915**
	1009.00)			
MACCEs (%, n)	15 (24.2%)	6 (14.3%)	9 (45.0%)	0.008

Table 5
Outcomes in PCI-treated patients by 3v-CT-FFR value

Age (year)	**Total**	**PCI + 3v-CT-FFR > 2.5 (*n* = 36)**	**PCI + 3v-CT-FFR ≤ 2.5 (*n* = 59)**	***P* value**
	61.68 ± 11.48	**58.00(51.00, 67.75)**	**65.00(53.00, 71.00)**	**0.966**
Male (%, n)	56 (58.9%)	20 (55.6%)	36 (61.0%)	0.600
Hypertension (%, n)	60 (63.2%)	21(58.3%)	39 (66.1%)	0.446
Diabetes (%, n)	21 (22.1%)	8 (22.2%)	13 (22.0%)	0.983
Atrial fibrillation (%, n)	4 (4.2%)	1 (2.8%)	3 (5.1%)	0.987
Cerebral infarction (%, n)	19 (20.0%)	6 (16.7%)	13 (22.0%)	0.526
Smoking history (%, n)	45 (47.4%)	18 (50.0%)	27 (45.8%)	0.688
Aspirin (%, n)	94 (98.9%)	36 (100%)	58 (98.3%)	0.432
Clopidogrel (%, n)	33 (34.7%)	14 (38.9%)	19 (32.2%)	0.507
Ticagrelor (%, n)	62 (65.3%)	22 (61.1%)	40 (67.8%)	0.507
Statins (%, n)	93 (97.9%)	36 (100%)	57 (96.6%)	0.704
ARNI (%, n)	46 (48.4%)	30 (50.8%)	16 (44.4%)	0.545
Glucose(mmol/L)	5.49(4.31, 6.35)	5.51 (4.30, 6.15)	5.42 (4.38, 6.76)	0.198
Uric acid(umol/L)	298.84 ± 84.56	298.81 ± 88.06	298.86 ± 83.09	0.672
Creatinine(umol/L)	67.00 (59.00, 75.00)	68.00 (58.25, 83.50)	67.00 (59.00, 71.00)	0.898
Total cholesterol(mmol/L)	3.70 (3.03, 4.41)	3.92 (3.28, 5.41)	3. 02(3.60, 4.16)	0.62
Triglycerides(mmol/L)	1.23(0.97, 1.92)	0.84 (1.20, 2.35)	1.30 (1.03, 1.80)	0.997
Low-density lipoprotein(mmol/L)	2.04 (1.57, 3.04)	2.51 (1.62, 3.30)	1.97 (1.54, 2.53)	0.425
High-density lipoprotein(mmol/L)	0.92(0.81, 1.18)	0.94 (0.83, 1.17)	0.89 (0.81, 1.20)	0.542
Lipoprotein a(mmol/L)	206.00 (101.00, 394.00)	280.00 (113.25, 416.50)	192.00 (100.00, 350.00)	0.36
N-terminal pro-B-type-natriuretic peptide(pg/ml)	68.50 (37.20, 162.00)	46.35 (32.65, 133.50)	75.60 (50.40, 169.00)	0.372

Age (year)	**Total**	**PCI + 3v-CT-FFR > 2.5 (*n* = 36)**	**PCI + 3v-CT-FFR ≤ 2.5 (*n* = 59)**	***P* value**
	61.68 ± 11.48	**58.00(51.00, 67.75)**	**65.00(53.00, 71.00)**	**0.966**
Creatine kinase(U/L)	61.00 (43.00, 82.00)	48.00 (37.50, 70.03)	65.00 (46.00, 95.00)	0.103
MACCEs (%, n)	43 (27.4%)	30 (38.0%)	13 (16.7%)	0.003
Survival time(day)	1117.00 (711.00, 1266.00)	1080.50 (775.00, 1276.50)	1140.00 (452.00, 1256.00)	0.432

Table 6
Comparison of clinical characteristics between the MACCEs and non-MACCEs groups

Age (year)	□□	**MACCEs(n = 43)**	**Non- MACCEs(n = 114)**	***P* value**
	61.71 ± 11.32	**62.95 ± 11.64**	**61.31 ± 11.19**	**0.417**
Male (%, n)	97 (61.8%)	32 (74.4%)	65 (57.0%)	0.045
Hypertension (%, n)	91 (58.0%)	24 (55.8%)	67 (58.8%)	0.738
Diabetes (%, n)	40 (25.5%)	23 (53.5%)	17 (14.9%)	<0.001
Atrial fibrillation (%, n)	9 (5.7%)	3 (7.0%)	6 (5.3%)	0.978
Cerebral infarction (%, n)	30 (19.1%)	10 (23.3%)	20 (17.5%)	0.417
Smoking history (%, n)	84 (53.5%)	30 (69.8%)	54 (47.4%)	0.012
Aspirin (%, n)	143 (91.1%)	41 (95.3%)	102 (89.5%)	0.402
Clopidogrel (%, n)	51 (32.5%)	18 (41.9%)	33 (28.9%)	0.123
Ticagrelor (%, n)	77 (49.0%)	22 (51.2%)	55 (48.2%)	0.744
Statins (%, n)	154 (98.1%)	42 (97.7%)	112 (98.2%)	>0.999
ARNI (%, n)	76 (48.4%)	22 (51.2%)	54 (47.4%)	0.671
Survival time(day)	30.00 (22.00, 38.00)	302.00 (149.00, 517.00)	1082.50 (860.75, 1242.25)	<0.001
PCI (%, n)	95 (60.5%)	28 (65.1%)	67 (58.8%)	0.468
Glucose(mmol/L)	5.35 (4.42, 6.23)	4.97 (4.38, 6.35)	5.38 (4.43, 6.15)	0.502
Uric Acid(umol/L)	295.00 (247.50, 345.00)	300.00 (267.00, 367.00)	294.00 (242.00, 343.00)	0.255
Creatinine(umol/L)	68.00 (59.00, 75.00)	70.00 (66.00, 81.00)	66.00 (57.50, 72.00)	0.005
Total cholesterol(mmol/L)	3.95 (3.16, 4.41)	3.94 (3.16, 4.07)	3.99 (3.17, 4.81)	0.364
Triglycerides(mmol/L)	1.42 (0.96, 1.75)	1.32 (0.87, 1.75)	1.43 (0.97, 1.77)	0.585
Low-density lipoprotein(mmol/L)	2.31 (1.72, 2.83)	2.31 ± 0.73	2.39 ± 1.03	0.672
High-density lipoprotein(mmol/L)	1.02 (0.86, 1.16)	0.96 ± 0.20	1.05 ± 0.23	0.027

Age (year)	□□	MACCEs(n = 43)	Non- MACCEs(n = 114)	*P* value
	61.71 ± 11.32	**62.95 ± 11.64**	**61.31 ± 11.19**	**0.417**
Lipoprotein a(mmol/L)	205.00 (104.50, 331.50)	229.00 (98.00, 422.00)	204.00 (105.00, 282.00)	0.462
N-terminal pro-B-type-natriuretic peptide(pg/ml)	115.50 (43.70, 241.81)	148.00 (65.10, 241.81)	103.00 (37.05, 241.81)	0.044
Creatine kinase(U/L)	87.50 (53.00, 93.50)	90.90 (58.00, 95.00)	79.00 (52.00, 90.95)	0.200

Table 7
Comparison of coronary lesion characteristics between the MACCEs and non-MACCEs groups

3v-CT-FFR ≤ 2.5 (%, n)	Total	MACCEs group (*n* = 43)	Non-MACCEs group (*n* = 114)	*P* value
	79 (50.3%)	**30 (69.8%)**	**49 (43.0%)**	**0.003**
Triple vessel CAD (%, n)	60 (38.2%)	28 (65.1%)	32 (28.1%)	< 0.001
Grace	97.73 ± 22.17	99.33 ± 24.54	97.12 ± 21.29	0.581
Gensini	32.00 (14.00, 52.75)	42.00 (20.00, 73.00)	28.00 (12.00, 46.00)	0.002

2.4 Survival Analysis and Multivariate Cox Regression Analysis

To evaluate the predictors of MACCEs, survival analysis and multivariate Cox proportional hazards regression analysis were performed. The occurrence of MACCEs was used as the dependent variable (coded as 1 for event occurrence and 0 for no event), and the following variables were included as independent factors: presence of diabetes mellitus, smoking status, serum creatinine level, number of diseased coronary vessels, and 3v-CT-FFR value. The results identified the following as independent predictors of MACCEs: (1) 3v-CT-FFR ≤ 2.5: hazard ratio (HR) = 4.121, 95% CI: 2.108–8.054, $P < 0.001$; (2) triple-vessel CAD: HR = 2.714, 95% CI: 1.362–5.407, $P = 0.005$; (3) diabetes mellitus: HR = 2.133, 95% CI: 1.094–4.159, $P = 0.026$; and (4) smoking: HR = 5.085, 95% CI: 1.851–13.965, $P = 0.002$. Kaplan–Meier survival analysis further demonstrated that patients with a 3v-CT-FFR > 2.5 had significantly longer long-term event-free survival than did those with a 3v-CT-FFR ≤ 2.5, which was supported by the log-rank test ($P < 0.05$). These findings indicate that a higher 3v-CT-FFR is associated with a more favorable mid- to long-term prognosis.

DISCUSSION

This study is the first to incorporate the sum of noninvasive CT-FFR values from the 3v-CT-FFR into the prognostic evaluation of patients with UA. A 3v-CT-FFR ≤ 2.5 was significantly associated with an increased long-term risk of MACCEs, demonstrating considerable predictive accuracy. Compared with single-vessel or anatomical scoring systems, the 3v-CT-FFR offers a more comprehensive representation of global functional imbalance in multivessel disease, thereby enhancing risk stratification for patients with UA.

Although CAG is widely regarded as the “gold standard” for diagnosing CAD and is extensively used in minimally invasive interventions, its inherent limitations should not be overlooked. CAG relies on two-dimensional angiographic projections and can display only the longitudinal section of the coronary lumen, making it difficult to reconstruct the three-dimensional spatial course of the vessel. Its assessment of stenosis is susceptible to variations in projection angles and reference vessel selection, and it provides purely anatomical information without quantitative evaluation of physiological function. Systematic reviews and meta-analyses have shown that approximately one-third of patients with visually significant stenosis on CAG do not exhibit evidence of myocardial ischemia; conversely, more than 10% of patients with nonsignificant anatomical narrowing do in fact have functionally significant ischemia [15]. These findings underscore the inadequacy of relying solely on anatomical stenosis to fully reflect myocardial perfusion status or to guide individualized interventional decisions. With the rapid development of intravascular imaging modalities, such as intravascular ultrasound and optical coherence tomography, and coronary physiological assessment techniques, such as FFR, quantitative flow ratio, and CT-FFR, integrated anatomical and perfusion assessment through multidimensional and multimodal approaches has become an inevitable trend in precision medicine [16–18]. Considering the role of significant myocardial ischemia in the selection of interventional therapy, there is an urgent need to complement routine CCTA or CAG with noninvasive or minimally invasive functional assessments, thereby facilitating more precise and individualized treatment strategies.

In current clinical practice, patients with CAD often present with multivessel involvement. Studies focusing on a single vessel are insufficient for comprehensively assessing the overall ischemic burden and its impact on MACCEs. Most previous CT-FFR research has concentrated on the functional evaluation of individual lesions or has explored prognostic implications using invasive 3v-FFR. However, several studies have demonstrated that quantifying overall lesion burden using the sum of FFR values from all three major coronary arteries (*i.e.*, 3v-FFR) can effectively distinguish between high- and low-risk populations for long-term adverse cardiovascular events. This prognostic difference is attributed primarily to the interplay between severely ischemic vessels and functionally preserved vessels [10, 19, 20]. Despite its clinical value, the wider use of the FFR is limited because of the procedural risks associated with adenosine administration and pressure wire manipulation. Recently, a multicenter study validated the prognostic significance of the three-vessel contrast-flow-based quantitative flow ratio (3V-cQFR) in a cohort of 549 patients with stable CAD. The results indicated that a lower 3V-cQFR was significantly associated with a greater incidence of MACCEs during the 2.2-year follow-up period. Multivariate analysis identified 3V-cQFR, high-sensitivity cardiac troponin I, and a history of myocardial infarction as

independent predictors of MACCEs. In contrast, traditional angiographic scoring systems did not demonstrate significant predictive power. The study confirmed that calculating 3V-cQFR from routine invasive CAG is not only feasible but also offers superior risk stratification capability compared with conventional angiographic assessment [21]. Nonetheless, the application of 3V-cQFR in high-risk outpatient noninvasive screening remains challenging. Building on the aforementioned findings, the global functional status of the coronary arteries has emerged as a key indicator of overall prognosis in patients with CAD, offering a robust physiological foundation for developing individualized treatment strategies. This study employed the deep learning–based CT-FFR algorithm DeepVESSEL-FFR to enable rapid, noninvasive global function assessment of the three major coronary arteries. The results indicated high concordance with invasive 3v-FFR while eliminating the need for adenosine-induced hyperemia or guidewire manipulation. This approach significantly broadens the clinical potential of functional assessment in UA management.

In this study, patients with newly diagnosed UA were included to investigate the association between a 3v-CT-FFR ≤ 2.5 and the occurrence of MACCEs. The results revealed that a 3v-CT-FFR ≤ 2.5 serves as a significant independent risk factor, indicating high sensitivity and specificity in predicting MACCEs. Further analysis revealed that patients with a 3v-CT-FFR ≤ 2.5 had a significantly greater incidence of MACCEs than did those with a 3v-CT-FFR > 2.5 (69.8% *vs.* 43.0%, $P = 0.003$). Notably, all deaths recorded in this study occurred in patients with a 3v-CT-FFR ≤ 2.5. Among the 79 patients with a 3v-CT-FFR ≤ 2.5, 59 underwent PCI, and their survival time was significantly longer than that of those who received conservative treatment ($P < 0.05$). Although there was no statistically significant difference in survival time between patients with a 3v-CT-FFR ≤ 2.5 and those with a 3v-CT-FFR > 2.5 among the 62 patients who did not undergo PCI, the incidence of MACCEs remained significantly greater in the 3v-CT-FFR ≤ 2.5 group. These findings suggest that further clinical intervention should be considered for patients with a 3v-CT-FFR ≤ 2.5. In addition, a total of 60 patients (38.2%) in this study had triple vessel disease. Among those without triple vessel involvement, a substantial proportion had double-vessel disease. Even after stent implantation in a single vessel, patients may still experience MACCEs, indicating that relying solely on a single-vessel CT-FFR value < 0.8 for clinical decision-making is insufficient. This highlights the necessity of conducting a more comprehensive evaluation that accounts for multivessel disease. Notably, while a 3v-CT-FFR > 2.5 is associated with a significantly reduced risk of adverse cardiovascular events, its application in clinical practice should still be weighed against the patient's overall condition, prognostic factors, and individualized treatment strategy. Therefore, a 3v-CT-FFR ≤ 2.5, as a novel functional assessment parameter, holds considerable clinical value in guiding individualized treatment and prognostic management for patients with CAD. Although coronary obstruction in patients with UA is significantly associated with the risk of developing MACCEs [22], anatomical stenosis does not always correlate with actual hemodynamic impairment. The use of 3v-CT-FFR values derived from CCTA allows for noninvasive and quantitative reconstruction of coronary hemodynamics, effectively addressing the limitations of purely anatomical assessments. Clinically, combining 3v-CT-FFR with individual patient characteristics enables the precise identification of high-risk populations and helps determine the optimal timing for safely deferring or avoiding invasive CAG, thereby reducing healthcare costs and

procedural complications. Consequently, for patients with newly diagnosed UA, an abnormal 3v-CT-FFR (≤ 2.5) detected on initial CCTA should prompt timely consideration of further functional validation or interventional therapy.

LIMITATIONS

First, this study adopted a retrospective cohort design, which may be subject to potential selection bias. Additionally, this study was conducted at a single center; therefore, the predictive value of the 3v-CT-FFR requires validation in multicenter, large-sample, prospective cohorts. Second, the CT-FFR measurements were based solely on the deep learning algorithm DeepVESSEL-FFR, without simultaneous comparisons with invasive indicators such as the wire-based FFR or the quantitative flow ratio. Thus, measurement discrepancies cannot be ruled out. Future studies should incorporate concurrent invasive FFR or hemodynamic modeling data to assess the accuracy and consistency of the CT-FFR and 3v-CT-FFR. Third, the 3v-CT-FFR was measured only once during CCTA and was not dynamically monitored during follow-up. Given that cardiac status and plaque characteristics may change over time or in response to pharmacological or interventional treatment, future studies may consider serial measurements or pre- and postintervention comparisons to explore dynamic trends and their prognostic implications. Fourth, this study did not incorporate multimodal parameters such as plaque composition, inflammation, or wall shear stress. Our focus was on functional assessment using the CT-FFR, without high-resolution plaque characterization using intravascular ultrasound or optical coherence tomography, limiting the development of a deeper understanding of the underlying pathophysiological mechanisms. Finally, patients with atrial fibrillation, arrhythmias, or other nonsinus rhythms were excluded; thus, the applicability of the 3v-CT-FFR in these high-risk populations remains unclear. Moreover, this cohort included only patients with UA and did not include those with stable or acute myocardial infarction. Therefore, further investigation is needed before generalizing these findings to patients with stable or acute myocardial infarction.

CONCLUSION

As a noninvasive and quantitative indicator of global coronary functional status, a summed 3v-CT-FFR ≤ 2.5 can be used to independently predict the long-term risk of MACCEs in patients with UA. This parameter provides a valuable basis for individualized interventional decision-making. Future multicenter, prospective studies are needed to validate its predictive utility and to explore its applicability across different subgroups of CAD patients, thereby advancing precision cardiovascular imaging and therapy.

Declarations

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Availability of data and materials

Individual participant data that underlie the results reported in thisarticle, after de-identification can be obtained from the corresponding author upon reasonable request.

Compliance with Ethical Standards

Guarantor

The scientific guarantor of this publication is Hongju Wang.

Conflict of Interest

The authors of this manuscript declare no relationships with anycompanies, whose products or services may be related to the subjectmatter of the article.

Informed Consent

Written informed consent was obtained from all subjects (patients) in this study.

Ethical Approval

This study was approved by the Ethics Committee of the First Affiliated Hospital of Bengbu Medical University ([2023]KY046).

Study subjects or cohorts overlap

None of.

Authors contributions

Zhuoya Yao conceived and performed the study. Jun Wang,Miaonan Li and Hongju Wang participated in the design of the study and performed the clinical study. Yao Li and Chuan Jin wrote the manuscript and analysis and interpretation of the data.All authors agree to be accountable for all aspects of the work

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Figures

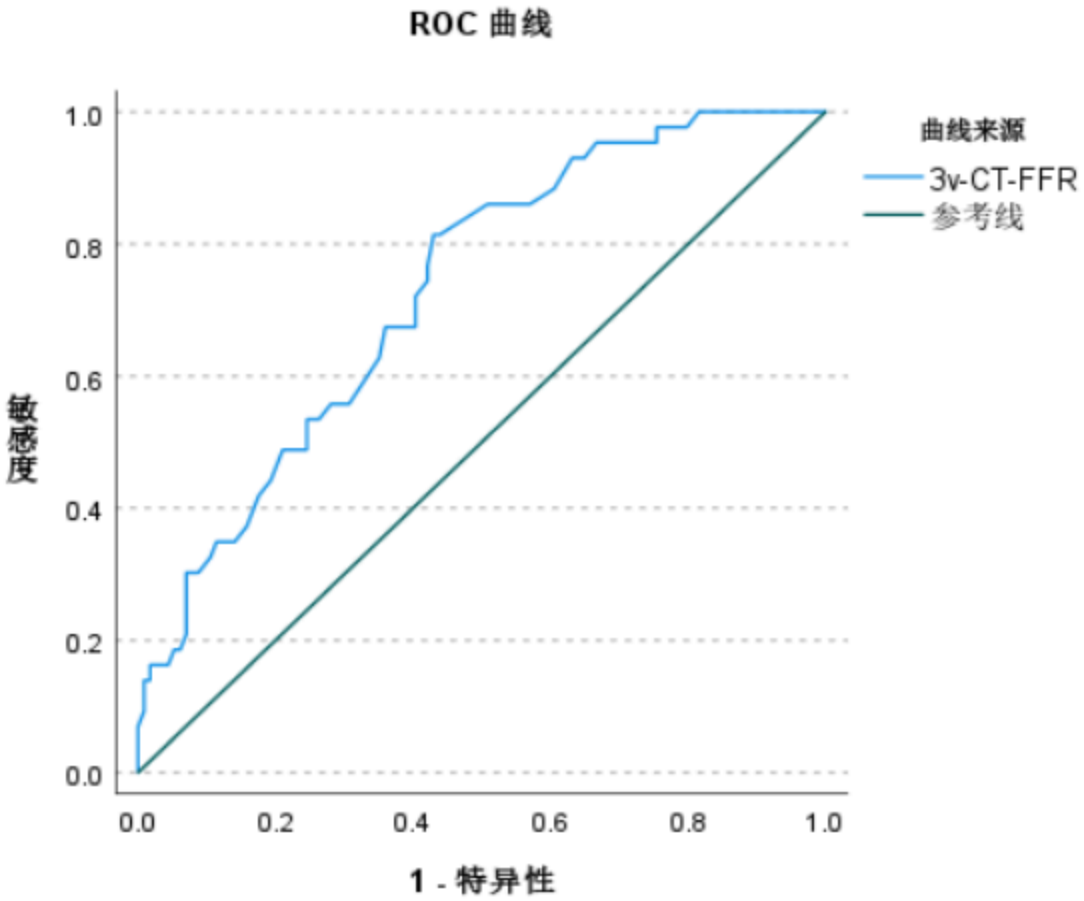


Figure 1

Unnumbered image in the Result section.

Exposure	P	Exp(B)	95.0%LCI	95.0%HCI
Three vascular lesions	0.005	2.714	1.362	5.407
2DM	0.026	2.133	1.094	4.159
Hlistory of stroke (%, n)	0.002	5.085	1.851	13.965
3v-CT-FFR≤2.5 or not	<0.001	4.121	2.108	8.054
CR	0.076	1.013	0.999	1.028

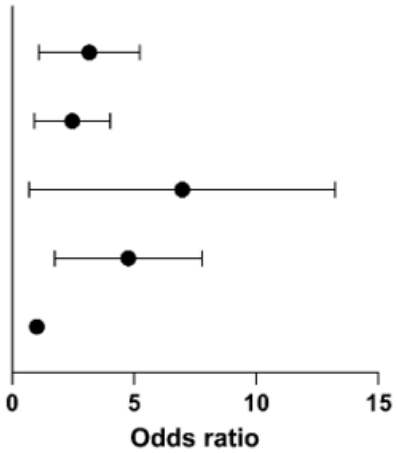


Figure 2

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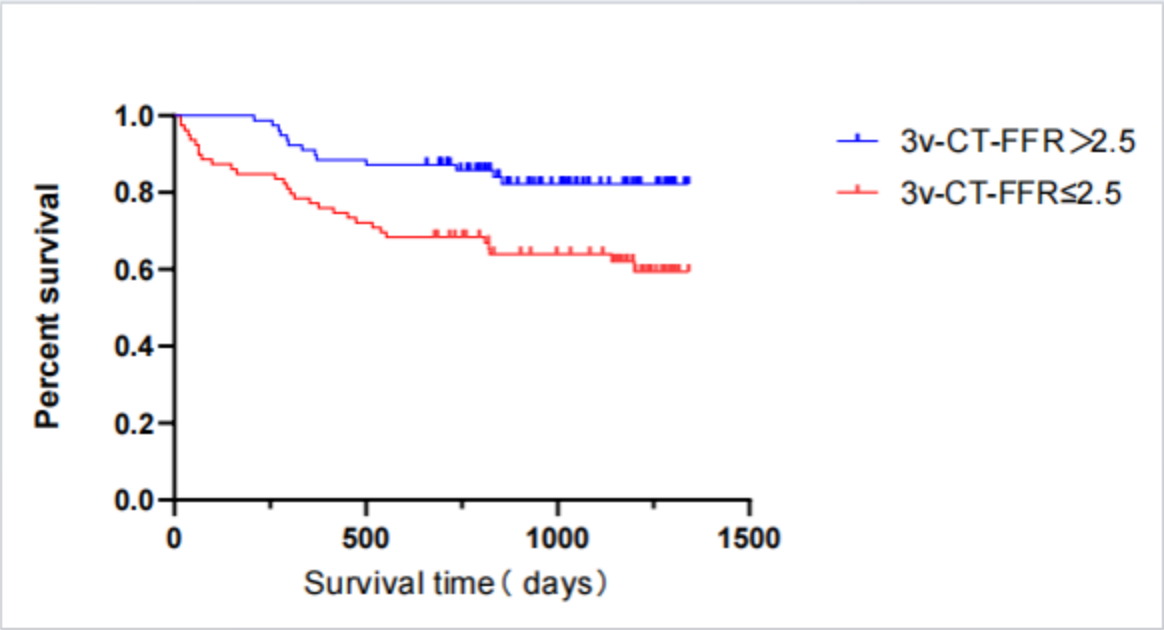


Figure 3

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