



CT血管造影多参数预测冠心病不良心脏事件的价值*

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【摘要】目的 探究基于CT血管造影(computed tomography angiography, CTA)的血流储备分数(fractional flow reserve, FFR)、脂肪衰减指数(fat attenuation index, FAI)及斑块特征对冠心病(coronary artery heart disease, CAD)患者主要不良心脏事件(major adverse cardiac events, MACE)发生的预测价值。**方法** 回顾性分析我院205例CAD患者资料,所有患者均进行CTA检查,测量其FFR、FAI及斑块特征,随访患者36个月内MACE的发生情况,将患者分为MACE组($n=42$)和非MACE组($n=163$),比较两组临床资料、FFR、FAI及斑块特征,采用logistic回归分析影响CAD患者并发MACE的相关因素;比较不同冠状动脉狭窄程度患者FFR、FAI及斑块负荷(plaque burden, PB),采用Spearman相关分析FFR、FAI及PB与CAD患者冠状动脉狭窄程度的相关性;采用受试者工作特征(receiver operating characteristic, ROC)曲线分析FFR、FAI及PB对CAD患者MACE的预测价值。**结果** MACE组体质量指数、两支及以上血管病变占比、重度狭窄占比、FAI、脂质斑块体积、非钙化斑块体积及PB均高于非MACE组($P<0.05$),FFR低于非MACE组($P<0.05$)。共线性诊断将方差膨胀因子 <3 的变量纳入多因素logistic回归分析,结果显示,多支病变[比值比(odds ratio, OR)=2.188, 95%置信区间(confidence interval, CI): 1.304 ~ 3.671]、冠状动脉重度狭窄(OR=2.918, 95%CI: 1.608 ~ 5.295)、FAI升高(OR=2.635, 95%CI: 1.510 ~ 4.598)、PB升高(OR=2.396, 95%CI: 1.382 ~ 4.157)是影响CAD患者发生MACE的危险因素(均 $P<0.05$),FFR升高(OR=0.373, 95%CI: 0.221 ~ 0.630)为保护因素($P<0.05$)。按冠状动脉狭窄程度分组,轻度组FFR高于中度组和重度组($P<0.05$),FAI、PB低于中度组和重度组($P<0.05$),中度组FFR高于重度组($P<0.05$),FAI、PB低于重度组($P<0.05$);Spearman相关分析显示,冠状动脉狭窄程度与FAI($r=0.687$, 95%CI: 0.598 ~ 0.760)及PB值($r=0.664$, 95%CI: 0.571 ~ 0.741)呈正相关($P<0.05$),与FFR($r=-0.712$, 95%CI: -0.782 ~ -0.628)呈负相关($P<0.05$)。ROC曲线分析显示,FFR、FAI及PB单独及联合检测预测CAD患者发生MACE的曲线下面积分别为0.831(95%CI: 0.750 ~ 0.876)、0.790(95%CI: 0.719 ~ 0.861)、0.724(95%CI: 0.646 ~ 0.802)、0.927(95%CI: 0.890 ~ 0.964),联合预测价值更高。**结论** 基于CTA的FFR、FAI及PB与CAD患者冠状动脉狭窄程度具有相关性,且联合检测对患者并发MACE具有较高的预测价值。

【关键词】 冠心病 CT血管造影 主要不良心脏事件 血流储备分数 脂肪衰减指数 斑块特征

Value of Multivariate Computed Tomography Angiography for Predicting Major Adverse Cardiac Events in Patients With Coronary Artery Heart Disease

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[Abstract] Objective To investigate the predictive value of computed tomography angiography (CTA)-derived fractional flow reserve (FFR), fat attenuation index (FAI), and plaque characteristics for the occurrence of major adverse cardiac events (MACE) in patients with coronary artery heart disease (CAD). **Methods** A total of 205 CAD patients were retrospectively enrolled at our hospital, and their demographic and clinical data were analyzed accordingly. All patients underwent CTA, and their FFR, FAI and plaque characteristics were measured. According to the occurrence of MACE within a 36-month follow-up period, the patients were divided into a MACE group ($n=42$) and a non-MACE group ($n=163$). The clinical data, FFR, FAI, and plaque characteristics were compared between the 2 groups, and logistic regression analysis was performed to identify factors associated with MACE in CAD patients. FFR, FAI, and plaque burden (PB) were further compared among patients with different degrees of coronary artery stenosis, and Spearman correlation analysis was performed to evaluate the associations of FFR, FAI, and PB with the severity of coronary artery stenosis. Receiver operating characteristic (ROC) curves were plotted to assess the predictive value of FFR, FAI, and PB for MACE in CAD patients. **Results** Compared with those in the non-MACE group, the body mass index (BMI), the

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proportion of patients with vascular lesions involving 2 or more coronary arteries, the proportion of patients with severe coronary stenosis, FAI, lipid plaque volume, non-calcified plaque volume, and PB were significantly higher (all $P < 0.05$) in the MACE group, whereas FFR was significantly lower ($P < 0.05$) in the MACE group. Variables with variance inflation factor (VIF) < 3 on collinearity diagnostics were included in multivariate logistic regression analysis. The results showed that multivessel lesion (odds ratio [OR], 2.188; 95% CI, 1.304-3.671), severe coronary artery stenosis (OR, 2.918; 95% CI, 1.608-5.295), increased FAI (OR, 2.635; 95% CI, 1.510-4.598), and increased PB (OR, 2.396; 95% CI, 1.382-4.157) were risk factors for MACE in CAD patients ($P < 0.05$), while increased FFR (OR, 0.373; 95% CI, 0.221-0.630) was a protective factor ($P < 0.05$). Stratified analysis by the severity of coronary artery stenosis showed that patients with mild stenosis had significantly higher FFR and significantly lower FAI and PB than those with moderate or severe stenosis (all $P < 0.05$), and that patients with moderate stenosis had significantly higher FFR and significantly lower FAI and PB than those with severe stenosis (all $P < 0.05$). Spearman correlation coefficient analysis revealed that the severity of coronary artery stenosis was positively correlated with FAI ($r = 0.687$; 95% CI, 0.598-0.760) and PB ($r = 0.664$; 95% CI, 0.571-0.741) ($P < 0.05$), but negatively correlated with FFR ($r = -0.712$; 95% CI, -0.782 to -0.628 ; $P < 0.05$). ROC curve analysis showed that the areas under the curve (AUCs) for predicting MACE in CAD patients using FFR, FAI, and PB individually were 0.831 (95% CI, 0.750-0.876), 0.790 (95% CI, 0.719-0.861), and 0.724 (95% CI, 0.646-0.802), respectively, whereas the combined model using the 3 parameters achieved an AUC of 0.927 (95% CI, 0.890-0.964), demonstrating superior predictive performance. **Conclusion** CTA-derived FFR, FAI, and PB are significantly correlated with the severity of coronary artery stenosis in patients with CAD. Combined assessment of these parameters demonstrates higher predictive value for the occurrence of MACE in patients with CAD.

[Key words] Coronary artery heart disease Computed tomography angiography Major adverse cardiac events
Fractional flow reserve Fat attenuation index Plaque characteristics

冠心病(coronary artery heart disease, CAD)是临床上较为常见的心血管疾病,其发病受多种因素影响,其中冠状动脉内皮损伤、脂质沉积及斑块形成、心肌血流灌注降低被认为是其主要病因^[1-2]。近年来,我国CAD发病率呈上升趋势,部分患者还并发多种主要不良心脏事件(major adverse cardiac events, MACE),目前,该病已成为威胁社会公共卫生安全的重要隐患被广泛关注^[3]。临床上主要通过影像学检查评估冠状动脉病变情况,其中,CT血管造影(computed tomography angiography, CTA)是CAD临床无创检查方式之一,通过CT扫描,可清晰显示狭窄情况及斑块特征,然而单纯的CTA检查主要提供冠状动脉的解剖结构,很难进行血流状况的定量评估^[4]。近年来,CTA在冠状动脉病变评估方面得到了较大突破。基于CTA的血流储备分数(fractional flow reserve, FFR)可提供冠状动脉的形态及功能学信息,准确评估冠状动脉狭窄及血流变化情况,对CAD患者心肌缺血具有良好的评估价值^[5]。脂肪衰减指数(fat attenuation index, FAI)可作为血管炎症的新型标志物用于评估心周脂肪组织的炎症状态,高FAI值与动脉粥样硬化风险相关^[6]。血管斑块是引起血管狭窄、CAD发病的重要因素,通过CTA检查可了解包括斑块分布、斑块成分、斑块形态特征等多个斑块特征指标,评估斑块的特性有助于预测CAD患者病情发展趋势^[7]。目前,三者辅助CAD病情评估方面的研究较多,而与患者预后的关系报道较少,基于此,本研究拟探究基于CTA的FFR、FAI及斑块特征在预测CAD患者

并发MACE中的应用价值。

1 资料与方法

1.1 研究对象

样本量计算方法:根据10 EPV原则^[8]计算拟纳入样本量,本研究分析的变量因素共17个,拟纳入170例,考虑5%的病例资料缺失或无效,最终纳入样本量205例。

回顾性分析2021年1月—2022年1月我院205例CAD患者资料。纳入标准:①符合CAD临床诊断标准^[9];②年龄 ≥ 18 岁;③均进行冠脉CTA检查;④未经经皮冠脉介入治疗;⑤患者病史及随访资料完整。排除标准:①既往有心脏手术史或先天性心脏病患者;②CTA图像质量不佳者;③CT-FFR分析失败者;④具有精神性疾病或认知异常者;⑤存在大量心包积液者。其中男117例,女88例,年龄42~90岁,平均(67.54 ± 10.33)岁。本研究遵循知情同意原则,并经核工业四一六医院医学伦理委员会审核批准(审查意见号:YJ-2024-039),批件有效期为一年。

1.2 一般资料收集

患者性别、年龄、体质量指数(body mass index, BMI)、合并症及随访资料均来自我院病历系统资料。

1.3 CTA检查

1.3.1 检查方法

患者取仰卧位,采用128排256层螺旋CT机(飞利浦,荷兰,型号:Brilliance iCT)及回顾性心电门控技术自气管分叉下方至心底1 cm进行扫描,采用高压注射器自肘静

脉以5 cm/s的速度注射50~70 mL碘帕醇(370 mg I/mL),注射完成后随即以相同速度注射30~40 mL生理盐水,设置管电压100 kV,管电流自动调节,准直器宽度80 mm,机架旋转时间0.27 s,层厚0.9 mm,层间隔0.45 mm。扫描结束后将所有数据上传至工作站进行后续处理。

1.3.2 图像处理及分析

所有患者于入院后72 h内行CTA检查。采用数坤科技数字心冠状动脉CTA AI辅助诊断软件进行一站式形态学评估,将CCTA DICOM序列导入CoronaryDoc工作站(软件版本CoronaryDoc 1.0.8),软件自动识别并加载数据,启动质控,软件全自动分割与三维建模,AI定位心脏、升主动脉、冠脉开口,深度学习模型自动追踪左主干、左前降支(left anterior descending branch, LAD)、左回旋支(left circumflex artery, LCX)、右冠状动脉(right coronary artery, RCA)及各级分支,自动建立三维冠脉树模型,提取中心线,分割管腔轮廓与斑块区域,并进一步自动识别:钙化/纤维/脂质斑块、狭窄程度、最小管腔面积、斑块负荷(plaque burden, PB),标记狭窄位置、长度、偏心/向心性,完成形态学评估-血管狭窄程度及斑块智能分析。

1.4 CTA检测指标

FFR、FAI、PB等结果的分析均由我院2名具有5年以上CTA诊断经验且未参与本次研究的影像科医师共同审核判定,以两者意见统一为最终评估结果,如意见相左则由第3名具有10年以上CTA诊断经验的高年资影像科医师介入共同探讨,直至得出一致结论。

1.4.1 FFR计算

集成于数坤CoronaryDoc数字心平台,数坤冠状动脉CT血流储备分数计算软件(DeepVessel-FFR/skCT-FFR,软件版本FFRDoc 1.0.8)自动识别冠状动脉中心线,生成三维模型,通过流体动力学模拟在最大充血状态下的流体力学参数,利用学习后的关系计算冠状动脉远端与主动脉根部的压力比值,获得目标血管的FFR值。

1.4.2 FAI测量

集成于数坤CoronaryDoc数字心平台,模块名称:Perivascular Fat Analysis Tool(冠周脂肪分析工具,软件版本EasyFAI 1.0.8),AI自动分割左主干、LAD、LCX、RCA三维血管树。定位每支血管近端40 mm段(FAI标准测量区)。冠周脂肪ROI自动提取以血管外膜为中心、径向距离等于血管直径的环形脂肪区域。AI自动勾画,排除钙化、血管、心肌、心包等非脂肪组织。范围:—190~—30 HU(脂肪组织CT值区间)。计算ROI内脂肪组织的加权平均HU值,并自动输出单支血管FAI、三支

血管平均FAI、最高FAI。

1.4.3 斑块特征分析

根据斑块体积计算PB,以病变血管分支上斑块总体积与该支血管总体积的比值作为PB。

1.4.4 血管狭窄程度分级^[10]

根据CTA测量的冠状动脉狭窄处直径与其周围正常血管直径的比值计算狭窄率,将狭窄率<50%、50%~69%、≥70%评为轻度狭窄、中度狭窄及重度狭窄。

1.5 MACE判定^[11]

以CTA检查为起点,每3个月通过门诊或电话的方式对患者进行随访,随访日期截至2025年1月,统计患者36个月内MACE的发生情况。MACE包括心源性死亡、心肌梗死、心力衰竭、不稳定性心绞痛,出现以上任意一项即可判定为MACE。

1.6 统计学方法

数据采用SPSS 26.0软件进行处理。计量资料以 $\bar{x} \pm s$ 表示,多组间比较采用单因素方差分析,组间两两比较采用LSD-*t*检验;计数资料以例数(%)描述,采用 χ^2 检验;相关性采用Spearman相关性分析;影响因素分析前使用共线性诊断筛选,将方差膨胀因子(variance inflation factor, VIF)<3的变量纳入多因素logistic回归分析,评估影响因素;预测价值采用受试者工作特征(receiver operating characteristic, ROC)曲线分析。 $\alpha=0.05$ 。

2 结果

2.1 MACE组和非MACE组临床资料比较

随访期间,共42例患者发生MACE,将205例患者分为MACE组($n=42$)和非MACE组($n=163$)。MACE组BMI、两支及以上血管病变占比、重度狭窄占比、FAI、脂质斑块体积、非钙化斑块体积及PB均高于非MACE组($P<0.05$),FFR值低于非MACE组($P<0.05$),见表1。

2.2 影响CAD患者发生MACE的多因素logistic回归分析

将上述有统计学意义的变量进行共线性诊断,见表2;以CAD患者并发MACE为因变量(1=是,0=否),将VIF<3的变量[病变支数(1=2支及以上,0=1支)、冠状动脉狭窄程度(0=轻度狭窄,1=中度狭窄,2=重度狭窄)、FFR(连续变量,无需赋值)、FAI(连续变量,无需赋值)、PB(连续变量,无需赋值)]纳入多因素logistic回归分析,结果显示,两支及以上血管病变[比值比(odds ratio, OR)=2.188, 95%置信区间(confidence interval, CI): 1.304~3.671]、冠状动脉重度狭窄(OR=2.918, 95%CI: 1.608~5.295)、FAI升高(OR=2.635, 95%CI: 1.510~4.598)、PB升高(OR=2.396, 95%CI: 1.382~4.157)

表 1 MACE组和非MACE组临床资料比较

Table 1 Comparison of clinical data between the MACE group and the non-MACE group

Clinical data	MACE group (n = 42)	Non-MACE group (n = 163)	χ^2/t	P
Sex/case (%)			0.503	0.478
Male	26 (61.90)	91 (55.83)		
Female	16 (38.10)	72 (44.17)		
Age/yr.	69.17 ± 10.55	67.12 ± 10.26	1.148	0.252
BMI/(kg/m ²)	25.61 ± 2.09	24.66 ± 2.12	2.597	0.010
Comorbidities/case (%)				
Hypertension	26 (61.90)	87 (53.37)	0.982	0.322
Diabetes mellitus	17 (40.48)	68 (41.42)	0.021	0.884
Hyperlipidemia	28 (66.67)	102 (62.58)	0.241	0.624
Lesion location/case (%)			0.224	0.894
Left anterior descending artery	23 (54.76)	92 (56.44)		
Left circumflex artery	12 (28.57)	41 (25.15)		
Right coronary artery	7 (16.67)	30 (18.40)		
Number of diseased vessels/case (%)			7.412	0.006
Single vessel	25 (59.52)	130 (79.75)		
Two or more vessels	17 (40.48)	33 (20.25)		
Degree of coronary stenosis/case (%)			22.703	< 0.001
Mild stenosis	8 (19.05)	92 (56.44)		
Moderate stenosis	20 (47.62)	29 (17.79)		
Severe stenosis	14 (33.33)	42 (25.77)		
Type of CAD/case (%)			5.831	0.120
STEMI	14 (33.33)	31 (19.02)		
NSTEMI	18 (42.86)	71 (43.56)		
Unstable angina	9 (21.43)	45 (27.61)		
Stable angina	1 (2.38)	16 (9.82)		
PCI/case (%)	18 (42.86)	49 (30.06)	2.485	0.115
Intravenous thrombolysis/case (%)	7 (16.67)	16 (9.82)	1.574	0.210
FFR	0.58 ± 0.16	0.81 ± 0.20	6.901	< 0.001
FAI/Hu	−73.61 ± 7.83	−84.13 ± 10.34	6.150	< 0.001
Lipid plaque volume/mm ³	21.65 ± 6.13	19.26 ± 5.52	2.459	0.015
Fibrous plaque volume/mm ³	73.22 ± 10.46	69.86 ± 10.56	1.842	0.067
Calcified plaque volume/mm ³	9.36 ± 2.23	8.56 ± 2.45	1.921	0.056
Non-calcified plaque volume/mm ³	83.27 ± 10.36	78.56 ± 9.65	2.778	0.006
PB/%	61.47 ± 6.57	55.20 ± 7.50	4.949	< 0.001

MACE: major adverse cardiac events; BMI: body mass index; CAD: coronary artery heart disease; STEMI: ST-segment elevation myocardial infarction; NSTEMI: non-ST-segment elevation myocardial infarction; PCI: percutaneous coronary intervention; FFR: fractional flow reserve; FAI: fat attenuation index; PB: plaque burden.

表 2 共线性诊断分析

Table 2 Diagnostic analysis of collinearity

Variable	Variance inflation factor (VIF)
BMI	3.932
Number of diseased vessels	1.865
Coronary stenosis severity	1.722
FFR	1.166
FAI	1.653
Lipid plaque volume	4.033
Non-calcified plaque volume	3.726
PB	1.967

The abbreviations are explained in the note to Table 1.

是影响CAD患者发生MACE的危险因素(均 $P<0.05$), FFR升高(OR=0.373, 95%CI: 0.221 ~ 0.630)为保护因素($P<0.05$), 见表3。

2.3 不同冠状动脉狭窄程度间FFR、FAI及PB比较

轻度狭窄组FFR高于中度狭窄组和重度狭窄组($P<0.05$), FAI、PB低于中度狭窄组和重度狭窄组($P<0.05$), 中度狭窄组FFR高于重度狭窄组($P<0.05$), FAI、PB低于重度狭窄组($P<0.05$), 见表4。

2.4 FFR、FAI及PB与冠状动脉狭窄程度的相关性分析

Spearman相关分析显示, 冠状动脉狭窄程度与FAI($r=$

表 3 影响CAD患者发生MACE的多因素logistic回归分析 (n=205)

Variable	β	SE	Wald χ^2	OR	P	95% CI
Number of diseased vessels (Ref: Single-vessel disease)	0.783	0.264	8.797	2.188	0.003	1.304-3.671
Coronary stenosis severity (Ref: Mild stenosis)						
Moderate stenosis	0.182	0.297	0.375	1.200	0.540	0.670-2.149
Severe stenosis	1.071	0.304	12.412	2.918	< 0.001	1.608-5.295
FFR	-0.986	0.267	13.637	0.373	< 0.001	0.221-0.630
FAI	0.969	0.284	11.642	2.635	0.001	1.510-4.598
PB	0.874	0.281	9.674	2.396	0.002	1.382-4.157

SE: standard error; OR: odds ratio; the other abbreviations are explained in the note to Table 1.

表 4 不同冠脉狭窄程度的CAD患者FFR、FAI及PB比较

Group	n	FFR	FAI/Hu	PB/%
Mild stenosis	100	0.84 ± 0.17	-85.89 ± 9.86	54.24 ± 5.53
Moderate stenosis	49	0.75 ± 0.14 ^a	-81.73 ± 10.17 ^a	56.84 ± 6.22 ^a
Severe stenosis	56	0.64 ± 0.16 ^{a,b}	-75.20 ± 8.53 ^{a,b}	60.18 ± 6.77 ^{a,b}
F		28.076	22.307	17.386
P		< 0.001	< 0.001	< 0.001

The abbreviations are explained in the note to Table 1. ^a P < 0.05, vs. mild stenosis group; ^b P < 0.05, vs. moderate stenosis group.

0.687, 95%CI: 0.598 ~ 0.760) 及PB($r=0.664$, 95%CI: 0.571 ~ 0.741)呈正相关($P<0.05$), 与FFR($r=-0.712$, 95%CI: -0.782 ~ -0.628)呈负相关($P<0.05$)。

2.5 FFR、FAI及PB对CAD患者发生MACE的预测价值分析

ROC 曲线分析显示 (图 1), FFR、FAI、PB、FFR+FAI+PB联合检测预测CAD患者发生MACE的曲线下面积分别为0.831(95%CI: 0.750 ~ 0.876)、0.790(95%CI: 0.719 ~ 0.861)、0.724(95%CI: 0.646 ~ 0.802)、0.927(95%CI: 0.890 ~ 0.964), 联合预测价值更高, 见表5。

3 讨论

冠状动脉粥样硬化性病变是CAD发病的主要原因, MACE是冠状动脉患者常见并发症, 不仅可加重患者病情, 增加治疗难度, 严重者可引发心力衰竭甚至死亡^[12]。研究发现, 冠状动脉血管狭窄、血流灌注降低、血管炎症、斑块形成等是引起MACE发病的重要因素^[13], 临床上

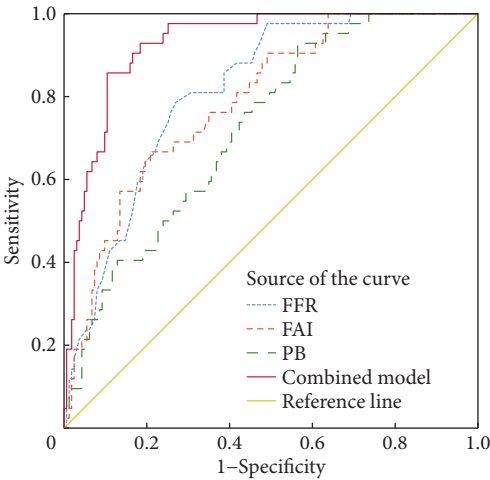


图 1 FFR、FAI及PB预测CAD患者发生MACE的ROC曲线
Fig 1 ROC curves of FFR, FAI, and PB for predicting the occurrence of MACE in patients with CAD

The abbreviations are explained in the note to Table 1.

通过疾病特征进行MACE预防具有一定的滞后性, 因而, 还需寻求更为敏感的指标预测早期MACE的发生。

表 5 FFR、FAI及PB对CAD患者发生MACE的预测价值分析 (n=205)

Indicator	AUC (95% CI)	Cut-off	Sensitivity/%	Specificity/%	Youden index
FFR	0.831 (0.750-0.876)	0.695	78.57	73.01	0.516
FAI	0.790 (0.719-0.861)	-77.80 Hu	78.57	66.87	0.454
PB	0.724 (0.646-0.802)	58.27%	76.19	67.48	0.437
Combined model	0.927 (0.890-0.964)	—	88.10	64.42	0.525

AUC: area under the curve; the other abbreviations are explained in the note to Table 1.

CTA可清晰显示冠状动脉形态特征、血流状况、斑块大小、斑块性质及血管狭窄情况,是目前临床上CAD患者临床检查的常用手段^[14-15]。基于CTA的FFR是反映血流状况的功能学指标,可用于评估冠状动脉狭窄引起的缺血性病变,且与一般解剖学反映的管腔狭窄相比更具临床意义^[16-17]。本研究多因素分析结果显示,FFR升高是MACE发生的保护因素(OR=0.373),提示FFR值每升高一个单位,MACE发生风险可降低约62.7%。研究显示,FFR值 ≤ 0.80 是CAD患者发生MACE的危险因素^[18],与本研究结果一致。冠状动脉周围脂肪组织与冠脉管壁相邻,可为冠状动脉提供物理性保护,减少因外部压力引起的血管损伤,同时,其还具有内分泌功能且代谢较为活跃,可分泌多种生物活性物质调节血管功能和炎症反应,当冠状动脉处于炎症状态时,其周围含水量较高,脂质含量较低,此时FAI值升高。除参与冠状动脉周围环境炎症调节外,FAI还可促进冠状动脉内斑块形成及不稳定斑块的破裂^[19-20]。本研究同样证实FAI升高是MACE的独立危险因素(OR=2.635)。朱铭等^[21]研究显示,重度血管狭窄或伴有钙化斑块的CAD患者FAI值较大,且高FAI值是CAD患者1年内发生MACE的独立危险因素。孙刚等^[22]研究显示,FAI升高、FFR值降低是冠状动脉粥样硬化患者并发MACE的独立危险因素,二者预测MACE的曲线下面积分别为0.695和0.771,联合预测曲线下面积为0.943,以上研究与本研究结论一致。斑块的形成是引起冠状动脉硬化的重要因素,CTA可显示管壁上的斑块信息,如斑块特征、分布特点、成分类型等,根据斑块体积计算病变血管的PB^[23]。本研究中心PB亦是MACE的独立危险因素(OR=2.396),提示PB越重,患者预后越差。研究发现,相较于稳定型斑块(如钙化斑块、纤维斑块),不稳定斑块(脂质斑块、非钙化斑块)破裂风险较高,更易引发MACE^[24]。PB反映斑块总体积占血管总体积的比例,其值越高表明病变血管内斑块体积越大,斑块占比升高可增加斑块脱落、内皮损伤、出血、血管阻塞等发生风险,因而,易导致MACE发生^[25]。

本研究纳入的205例CAD患者中,经随访,42例出现MACE,占比20.49%。对比发现,MACE组患者的两支及以上血管病变及重度狭窄血管占比更高,提示冠脉血管病变加重可加大MACE发病风险。FFR可判断冠状动脉病变引起的血流动力学波动情况,MACE组FFR值更低,表示患者血流动力较弱,引起心肌缺血性坏死的风险也就越高。FAI是反映冠状动脉炎症负担的指标,MACE组FAI值升高提示冠状动脉炎症负担加重,冠周水肿及冠状动脉狭窄的风险升高。此外,冠状动脉炎症也能促进脂质斑块形成,脂质斑块占血管总体积比例越高则冠状动脉堵塞更严重,

加剧血流灌注障碍,局部缺血缺氧则促进炎症反应增强,三者可形成恶性循环,促进CAD冠状动脉损伤增加,诱导MACE形成^[26]。本研究相关性分析也发现,FFR、FAI及PB值均与冠状动脉狭窄程度呈明显相关性,进一步说明了上述指标对CAD患者病情进展的评估作用。本研究结果还显示,MACE组脂质斑块、非钙化斑块体积更大,说明富含脂质的斑块更易受炎症刺激而加快溶解,进而加重冠状动脉堵塞风险,钙化斑块、纤维斑块除长期影响冠状动脉血流灌注外,其溶解风险较低,对病情进展的影响相对较低。随着PB加重,冠状动脉病变程度加深,患者病情进展更快,发生MACE的风险也就相对较高。经ROC曲线分析,FFR、FAI及PB联合预测CAD患者MACE发生的效能更高(曲线下面积为0.927),提示在临床实践中,对于CAD患者,可在常规CTA评估基础上,整合FFR、FAI及PB三个指标进行综合分析。这种联合评估策略有助于更精准识别MACE高风险人群,从而制定个体化的随访计划(如缩短随访间隔、强化药物治疗)和更具针对性的干预措施(如更早地进行血运重建评估),实现从单纯解剖学评估向功能学、炎症及斑块稳定性综合评估的转变,最终改善患者预后。然而,本研究为单中心小样本量研究,代表性有所欠缺,未来还需扩大样本量并联合其他医疗机构进行多中心大样本量研究,对本研究结果加以验证。

综上所述,基于CTA的FFR、FAI及PB值与CAD患者冠脉狭窄程度具有相关性,且联合检测对患者并发MACE具有较高的预测价值。

* * *

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Author Contribution Tu Bo is responsible for conceptualization, data curation, formal analysis, funding acquisition, writing--original draft, and writing--review and editing. Xiao Weiliang is responsible for investigation. Pan Zhihua is responsible for methodology. Liu Jia is responsible for project administration. Xiao Ke is responsible for resources and software. Li Hongcheng is responsible for supervision. Li Jian, Zhao Dechun, and Xie Hongying are responsible for validation. Liu Dongmei is responsible for visualization. All authors consented to the submission of the article to the Journal. All authors approved the final version to be published and agreed to take responsibility for all aspects of the work.

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