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Hans汉斯

# 胰岛素抵抗及其新型替代指标在心血管疾病中的作用：叙述性文献综述

何　烨[1*]，肖建民[2#]

[1]暨南大学附属第一医院心血管内科，广东　广州
[2]暨南大学第一临床医学院，广东　广州

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## 摘　要

**心血管疾病(CVD)是全球主要的致死原因之一，胰岛素抵抗(IR)作为其独立风险因素，即使在非糖尿病人群中亦然，通过中断胰岛素信号通路(如PI3K/Akt途径)、促进内皮功能障碍、氧化应激、炎症和血栓形成等机制，加速动脉粥样硬化和CVD进展。传统IR评估方法如高胰岛素正常血糖钳夹试验(HEC)和稳态模型评估胰岛素抵抗指数(HOMA-IR)操作复杂且成本高昂，限制其临床和流行病学应用。本综述通过PubMed数据库检索关键词“insulin resistance”“cardiovascular disease”“triglyceride-glucose index”和“METS-IR”，纳入叙述性综述、荟萃分析、队列研究和回顾性研究，旨在回顾IR在CVD中的病理生理作用，评估新型非胰岛素依赖替代指标如甘油三酯－葡萄糖指数(TyG指数)和胰岛素抵抗代谢评分(METS-IR)的进展，并识别现有知识缺口。结果显示，TyG指数与高血压、动脉硬化、动脉粥样硬化性心血管疾病(ASCVD)风险、冠心病(CAD)严重程度和预后(如主要不良心血管事件，MACE)显著相关，并可提升GRACE评分的预测价值(如AUC增加)；METS-IR在某些研究中优于TyG指数预测CAD严重程度，但两者比较结果不一致，一些研究支持TyG在预后评估中的优势。现有证据主要基于观察性研究，异质性高、人群偏倚明显(多局限于亚洲人群)。未来需开展多民族纵向队列研究、头对头比较以及随机对照试验，验证这些指标的临床转化价值，以指导CVD风险分层和个性化干预。**

## 关键词

**胰岛素抵抗，心血管疾病，甘油三酯－葡萄糖指数，胰岛素抵抗代谢评分，动脉粥样硬化，心血管预后**

# The Role of Insulin Resistance and Its Novel Surrogate Indexes in Cardiovascular Disease: A Narrative Literature Review

**Ye He[1*], Jianmin Xiao[2#]**

[*]第一作者。
[#]通讯作者。

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[1]Department of Cardiology, The First Affiliated Hospital of Jinan University, Guangzhou Guangdong
[2]The First Clinical Medical College of Jinan University, Guangzhou Guangdong

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## Abstract

**Cardiovascular disease (CVD) is one of the leading causes of death worldwide. Insulin resistance (IR), as an independent risk factor for CVD—even in non-diabetic populations—accelerates atherosclerosis and CVD progression by disrupting insulin signaling pathways (such as the PI3K/Akt pathway) and promoting endothelial dysfunction, oxidative stress, inflammation, and thrombosis. Traditional IR assessment methods, such as the hyperinsulinemic-euglycemic clamp (HEC) and the homeostasis model assessment of insulin resistance (HOMA-IR), are operationally complex and costly, limiting their clinical and epidemiological applications. This review searched the PubMed database using keywords "insulin resistance", "cardiovascular disease", "triglyceride-glucose index", and "METS-IR", and included narrative reviews, meta-analyses, cohort studies, and retrospective studies. It aims to review the pathophysiological role of IR in CVD, evaluate the progress of novel non-insulin-dependent surrogate markers such as the triglyceride-glucose index (TyG index) and the metabolic score for insulin resistance (METS-IR), and identify existing knowledge gaps. Results show that the TyG index is significantly associated with hypertension, arterial stiffness, atherosclerotic cardiovascular disease (ASCVD) risk, coronary artery disease (CAD) severity, and prognosis (such as major adverse cardiovascular events, MACE), and can enhance the predictive value of the GRACE score (e.g., increased AUC). METS-IR outperforms the TyG index in predicting CAD severity in some studies, but comparison results between the two are inconsistent, with some studies supporting the superiority of TyG in prognostic assessment. Existing evidence is primarily based on observational studies, with high heterogeneity and evident population bias (mostly limited to Asian populations). In the future, multiethnic longitudinal cohort studies, head-to-head comparisons, and randomized controlled trials are needed to validate the clinical translational value of these indicators, in order to guide CVD risk stratification and personalized interventions.**

## Keywords

**Insulin Resistance, Cardiovascular Disease, Triglyceride-Glucose Index, Metabolic Score for Insulin Resistance, Atherosclerosis, Cardiovascular Prognosis**



## 1. 引言

心血管疾病(cardiovascular disease, CVD)是全球主要的致死原因之一，每年导致约 1790 万人死亡，占总死亡人数的 32% [1]。胰岛素抵抗(insulin resistance, IR)作为代谢综合征的核心组成部分，被广泛认定为 CVD 的独立风险因素，即使在非糖尿病人群中亦然[2] [3]。IR 指靶组织对胰岛素作用的敏感性降低，导致高血糖和高胰岛素血症，进而促进内皮功能障碍、氧化应激、炎症和血栓形成。这些机制共同加速了动脉粥样硬化和 CVD 进展[1] [3]。传统 IR 评估方法，如高胰岛素正常血糖钳夹试验(hyperinsulinemic-euglycemic clamp, HEC)和稳态模型评估胰岛素抵抗指数(homeostasis model assessment of insulin resistance, HOMA-IR)，虽精确但操作复杂且成本高昂，限制了其在临床和流行病学中的应用[2] [4]。近年来，非胰岛素依赖的胰岛

素抵抗替代指标逐渐兴起，如甘油三酯－葡萄糖指数(Triglyceride-Glucose Index, TyG 指数)和胰岛素抵抗代谢评分(Metabolic Score for Insulin Resistance, METS-IR)，这些指标基于常规生化参数计算，已经展示出在预测 IR、糖尿病和 CVD 风险方面的潜力[5] [6]。本综述采用关键词“insulin resistance”“cardiovascular disease”“triglyceride-glucose index”和“METS-IR”，通过 PubMed 数据库检索英文文献，纳入叙述性综述、荟萃分析、队列研究和回顾性研究，旨在回顾 IR 在 CVD 中的病理生理作用，评估 TyG 指数和 METS-IR 等新型 IR 替代指标的研究进展，并识别现有知识缺口，为未来临床实践和研究方向提供些许见解。

## 2. IR 在 CVD 中的病理生理学作用

### 2.1. IR 的定义与 CVD 病理生理机制

IR 定义为胰岛素促进葡萄糖摄取和利用的效率降低，是代谢紊乱和全身炎症的标志物[7]。IR 被认为是由于胰岛素反应细胞暴露于缺氧、过量糖分、某些类型的脂肪酸、环境污染物或应激和肥胖期间释放的激素等各种细胞应激和应激反应之间的协同作用而产生的。从分子水平分析，IR 主要通过中断胰岛素信号通路如磷脂酰肌醇 3-激酶/蛋白激酶 B (PI3K/Akt)途径，导致内皮一氧化氮合成酶(eNOS)活性降低，从而减少一氧化氮(NO)产生，促进血管内皮功能障碍和炎症反应[8] [9]。研究表明，IR 是动脉粥样硬化早期阶段的关键病理生理过程[10]。IR 导致动脉粥样硬化斑块的形成的机制包括以下几个方面：IR 导致高血糖，从而激活炎症过程并引起氧化应激，最终导致血管内皮损伤[8]。它还可诱发血脂异常[8]。并且可直接刺激血管平滑肌细胞增殖和迁移至内膜，导致内皮功能障碍，并参与纤维帽的形成[11]。与此同时，胰岛素信号在血管内膜细胞(包括内皮细胞、吞噬细胞和平滑肌细胞)之间的转导中断也可能导致动脉粥样硬化[9]。以往的研究还发现 IR 可通过一系列分子机制导致心脏功能障碍，包括心肌－内皮相互作用失调、线粒体功能障碍、氧化应激、钙信号受损、底物代谢改变和内质网应激[12]。此外，与 IR 相关的高甘油三酯血症和高血糖与纤溶活性降低和血栓形成活性增加有关[13]。因此，IR 也被认为是急性冠状动脉综合征患者微血管和心肌损伤的原因[14]。研究还发现，IR 与心肌灌注不良和更大的梗死面积相关，这两者都被认为是 ST 段抬高型心肌梗死(ST-segment elevation myocardial infarction, STEMI)患者死亡率的预测因素[15]。尽管这些机制已经在动物模型中得到支持，但仍需得到更多人类队列研究验证以澄清因果关系。总的来说，胰岛素抵抗已被广泛证明与炎症反应、内皮功能障碍、凝血失衡、氧化应激、心肌再灌注不良、微循环功能障碍、斑块易损性和心血管重塑显著相关[8] [15]-[17]，这些病理反应和状态都介导了心血管疾病的发生和不良预后。因此，IR 不仅被确定为糖尿病的主要发病机制，也是心血管疾病发生和预后的重要危险因素[18]-[22]。

### 2.2. 传统 IR 评估方法(HEC 与 HOMA-IR)的介绍与局限

由 DeFronzo 等人[4]开发的 HEC，被广泛认为是直接测定人体胰岛素抵抗/敏感性的金标准[23]-[25]。但因为成本高昂、相对耗时及操作复杂的特点，该试验不仅在大型流行病学调查中难以实施、也无法广泛应用于临床实践中[26]-[28]。基于空腹胰岛素和血糖计算的 HOMA-IR 是一种用于研究葡萄糖与胰岛素动态变化之间相关性的模型[29]。作为另一种成熟的评估胰岛素抵抗的方法[24] [28]，其容易受外源胰岛素使用的影响，而且由于空腹胰岛素浓度在临床实践中并不常规测量，该模型同样不适用于广泛的临床应用[30] [31]。

## 3. 新型 IR 替代指标与 CVD 的关联：研究进展与知识缺口

### 3.1. TyG 指数作为 IR 的简单替代指标

鉴于 HEC 和 HOMA-IR 等传统 IR 评估方法的缺陷，有研究人员提出采用 TyG 指数[32]作为 IR 的简

单可靠替代指标。TyG 指数使用以下公式计算：TyG 指数 = ln[甘油三酯(mg/dL) × 空腹血糖(mg/dL)/2]。其易于计算，不需要特定技术和不常见参数，有利于临床应用。该指数能够很好地反映脂毒性和糖毒性状态[33] [34]。具体而言，TyG 指数中的甘油三酯成分反映了脂毒性，该毒性通过诱导氧化应激和炎症反应，促进内皮功能障碍和动脉粥样硬化[7] [8]；而空腹血糖成分则体现了糖毒性，即高血糖激活炎症过程并引起血管内皮损伤[7] [8]。此外，与 IR 相关的高甘油三酯血症可降低纤溶活性并增加血栓形成[13]，从而加速 CVD 进展。Sánchez-García, A 等人[35]在对 15 项研究中的 69,922 名患者进行的荟萃分析中表明，TyG 指数在诊断胰岛素抵抗方面的灵敏度为 96%，其它几项研究结果同样显示出该指数与 HEC 和 HOMA-IR 有良好的相关性[36]-[38]，无论是在有或没有 2 型糖尿病的个体中[32] [39] [40]。因此，TyG 指数作为便捷良好的胰岛素抵抗指标是可靠的[32]-[34] [36] [41]-[44]。甚至部分研究结果还表明 TyG 指数在评估胰岛素抵抗[44] [45]和预测动脉粥样硬化方面优于 HOMA-IR [43] [46]。

### 3.2. TyG 指数与 CVD 风险和严重程度的关联研究

近年来，TyG 指数与 CVD 之间的关系的研究在逐渐增加。Yang 等人[47]纳入 35,848 名参与者的 7 项队列研究进行荟萃分析后结果显示 TyG 指数的升高显著增加了普通人群中新发高血压的风险，并且亚组分析表明 TyG 指数与高血压之间的关系不受年龄、性别、身体质量指数(Body Mass Index, BMI)、参与者种族和随访时间的显著影响(交互作用的 P 值均 > 0.05)；Lukito 等人[48]的荟萃分析进一步指出 TyG 指数与高血压以非线性剂量反应方式强烈相关。Zhang 等人[49]招募了 1979 名参与者进行队列研究，还纳入 13 项研究进行荟萃分析，结果表明高 TyG 指数与增加的动脉硬化程度风险相关，该指数可以作为亚临床动脉粥样硬化和动脉硬化风险增加的独立预测因子，该研究的动脉硬化程度通过臂踝脉搏波速度(Brachial-Ankle Pulse Wave Velocity, baPWV)检查得出；另外的 2 篇荟萃分析也得出类似的结论[50] [51]。一项包括 8 项队列研究，共涉及 5,731,294 名参与者的荟萃分析结果显示：无论将 TyG 指数作为分类变量还是连续变量，较高的 TyG 指数可能与基线无动脉粥样硬化性心血管疾病(atherosclerotic cardiovascular disease, ASCVD)的人群中 ASCVD 的更高发病率独立相关，亚组分析进一步表明 TyG 指数与随后 ASCVD 发病率之间的关联不受参与者的年龄、性别或糖尿病状态的显著影响[52]。一项目的在于研究 TyG 指数与冠心病(Coronary Artery Disease, CAD)风险、严重程度和预后的系统回顾和荟萃分析表明与 TyG 指数较低的患者相比，TyG 指数较高的患者 CAD 风险更高、冠状动脉病变更严重、预后更差；该研究对于 CAD 严重程度的分析，结局包括冠状动脉钙化、冠状动脉狭窄、冠状动脉斑块进展、多支血管 CAD 和支架内再狭窄；对于 CAD 预后的分析，主要结局是主要不良心血管事件(Major Adverse Cardiovascular Events, MACE) [53]。Jiang 等人纳入 5 篇文章、共包含 3912 名参与者的旨在研究 TyG 指数与支架内再狭窄(In-Stent Restenosis, ISR)之间的关系的荟萃分析结果显示 TyG 指数与 ISR 显著相关，TyG 指数升高的患者 ISR 的倾向更高，而且亚组分析表明这种关联不受冠心病类型的影响[54]。甚至研究者还发现纳入 5 项研究(土耳其 2 项、中国 3 项)、共 3518 名患者(年龄范围：57.6 至 68.22 岁)，在调整了糖尿病和肾功能等潜在混杂因素后，TyG 指数与经皮冠状动脉介入治疗后造影剂诱发肾病的风险显示出显著的相关性[55]。

这些荟萃分析表明 TyG 指数与高血压、动脉硬化和 ASCVD 的关联强劲，但多数研究集中在亚洲人群，异质性高，可能受出版偏倚和观察性设计影响。并且需要注意到亚组分析的局限性，如未充分考虑混杂因素的交互作用。未来应开展全球多民族纵向研究以提升证据强度。

### 3.3. TyG 指数在 CAD 预后中的相关性

特别值得注意的是 TyG 指数与 CAD 预后的相关性研究。例如 Akbar 等人[56]纳入了 4 项研究中的 13,684 名受试者，进行荟萃分析显示，TyG 指数最高类别与急性冠脉综合征(Acute Coronary Syndrome, ACS)

患者 MACE 两倍相关(RR 2.09 [1.59, 2.76])。另外一项共纳入 21 个队列，包括 20,403 名个体的荟萃分析结果显示与 TyG 指数最低类别的个体相比，最高 TyG 类别的患者表现出更高的主要不良心脑血管事件(Major Adverse Cardiac and Cerebrovascular Events, MACCEs) ($P < 0.00001$)和全因死亡($P < 0.00001$)风险，这些发现与作为连续变量分析的 TyG 指数一致(MACCEs：$P = 0.006$；全因死亡：$P < 0.00001$)；亚组分析表明，糖尿病状态、急性心肌梗死(Acute Myocardial Infarction, AMI)类型和再灌注治疗均未破坏这种相关性[57]。

最后 Sun 等人在一项共纳入了 9 项队列研究、样本量从 515 到 2055 不等、随访时间均超过 12 个月的旨在研究 TyG 指数与中国经皮冠状动脉介入治疗后心血管预后的关系的荟萃分析结果提示 TyG 指数每增加一个单位，MACE 的风险比(Hazard Ratio, HR)为 1.82 (95% CI 1.34~2.46)，非致命性心肌梗死(Myocardial Infarction, MI)的 HR 为 2.57 (95% CI 1.49~4.41; $I^2 = 63\%$)，血管重建的 HR 为 2.06 (95% CI 1.23~3.50; $I^2 = 90\%$)。TyG 指数与 MACE 风险之间建立了线性关系($R^2 = 0.6114$)，全因死亡的 HR 为 1.93 (95% CI 1.35~2.75; $I^2 = 50\%$)。高 TyG 指数与 PCI 后 MACE、非致命性 MI、全因死亡和血管重建均有强烈的相关性[58]。

这些荟萃分析强调 TyG 指数在预测冠心病预后中的价值，但研究存在的高异质性、短期随访和特定人群(如中国患者)偏倚等不足，可能限制其在全球的推广应用。未来需考虑混杂因素如治疗差异等，并且有必要通过随机对照试验验证其作为独立预测指标的可靠性。

### 3.4. TyG 指数与风险模型的整合及其预测增量价值

在 Sun 等人的荟萃分析中，与纳入的 6 篇文章中将 TyG 指数与由互相之间并不完全相同的常见冠状动脉粥样硬化危险因素如年龄、性别、BMI、吸烟史、高血压、血脂异常等组成的基线模型结合后加以分析 TyG 指数对基线模型预测不良预后的增量价值[59]-[61]、或仅采用多变量模型分析 TyG 指数与终点事件的独立相关性[62]-[64]的做法不同，纳入的另外 3 篇文章在分析 TyG 指数的预测增量价值的过程中主要是直接联合了 TyG 指数与全球急性冠脉事件注册研究评分(Global Registry of Acute Coronary Events, GRACE) [65]-[67]。其它 4 篇[68]-[71]未纳入该荟萃分析的具有类似研究目的的文章也表明 TyG 指数与经皮冠状动脉介入治疗(Percutaneous Coronary Intervention, PCI)后 MACE 具有相关性，TyG 指数可作为 PCI 术后 MACE 的预测因子。

上述 13 篇文章中的 3 篇主要联合了 TyG 指数和 GRACE 评分进行分析接受经皮冠状动脉介入治疗患者不良心血管预后的文章均表明 TyG 指数对 GRACE 评分的不良心血管事件预测能力具有增益作用(AUC：GRACE 评分 0.798 vs. GRACE 评分 + TyG 指数 0.849 [67]、AUC：GRACE 评分 0.712 vs. GRACE 评分 + TyG 指数 0.751 [66]、C 统计量值从 0.735 增加到 0.744 [68])。

另外 Wang 等人[69]的研究结果显示在 TyG 和中性粒细胞与淋巴细胞比值(Neutrophil-to-Lymphocyte Ratio, NLR)均是 STEMI 患者 PCI 术后院内 MACE 的独立危险因素的前提下、TyG 和 NLR 结合传统预测模型 GRACE 评分具有更高的诊断价值(AUC：GRACE 评分 0.749 vs. GRACE 评分 + TyG 指数 + NLR 指数 0.839)，而 Ma 等人[71]的研究表明当超敏 C 反应蛋白(High-Sensitivity C-Reactive Protein, hsCRP)水平低于 2 mg/L 时，TyG 指数与 MACE 可靠且独立相关，TyG 指数和 hsCRP 两者的加入对基于 GRACE 评分的 MACE 预后模型的预测能力有增量作用(C 统计量：从 0.631 增加到 0.661)。

这些研究显示出 TyG 指数对 GRACE 评分有明显的增益作用，但还存在样本规模小、随访时间短，且主要为回顾性设计、可能存在选择偏倚等问题。这些不足要求开展更多前瞻性研究以评估其在不同 CAD 亚型中的预测增量价值。

### 3.5. METS-IR 作为新型 IR 替代指标及其与 TyG 指数的比较

作为 IR 的另外一种简单可靠替代指标[72]，METS-IR 可根据以下公式计算得出：METS-IR = [ln(2 ×

空腹血糖(mg/dL) + 甘油三酯(mg/dL)) × BMI (kg/m$^2$)]/ln(高密度脂蛋白胆固醇(mg/dL))。METS-IR 的组分进一步整合了 IR 的多维病理环节：空腹血糖和甘油三酯分别反映了糖毒性和脂毒性，与氧化应激、炎症和血栓形成相关[8] [13]；BMI 可反映整体肥胖风险，虽因无法区分脂肪分布，不能单独代表中心性肥胖，但与中心性肥胖高度相关；而中心性肥胖以内脏脂肪堆积为核心，通过释放激素(如瘦素、TNF-$\alpha$)和游离脂肪酸等应激因子，协同诱导 IR [7]；而高密度脂蛋白胆固醇的倒数则捕捉了脂质异常状态，该异常状态常伴随 IR 并促进动脉粥样硬化[8]。有研究表明就 C-统计量而言，在基线风险预测模型中加入 METS-IR 后，MACE 的风险预测显著改善(C-统计量从 0.71 增加到 0.72)，提示在基线风险预测模型中加入 METS-IR 可提高早发性 CAD 患者 MACE 的预后能力[73]。但该指数在与 CVD 关系的研究当中大多数情况下以与其他新型非胰岛素相关的 IR 指标如 TyG 指数、甘油三酯/高密度脂蛋白胆固醇比值(Triglycerides/High-Density Lipoprotein Cholesterol Ratio, TG/HDL-C)等相比较的形式出现，其中 METS-IR 和 TyG 指数对研究 CVD 的价值比较结果在不同研究之间也不尽相同。

一方面，研究结果支持 METS-IR 优于 TyG 指数的如下：一项旨在分析 TG/HDL-C、TyG 指数和 METS-IR 与 CAD 的关系，并对各指标的预测价值进行比较的研究结果显示：TG/HDL-C、TyG 指数和 METS-IR 是 CAD 存在和严重程度的有价值的预测因子。受试者工作特征曲线(Receiver Operating Characteristic Curve, ROC)分析显示，METS-IR 对 CAD 的存在和严重程度的预测价值最高(METS-IR [AUC (95% CI): 0.636 (0.589~0.683)]与 TG/HDL-C [0.567 (0.517~0.618)]和 TyG 指数[0.562 (0.509~0.614)]) [74]。Zhang 等人[75]在目的是探讨四种非胰岛素基础的 IR 指标在预测 CAD 严重程度方面的表现的研究中，调整混杂因素后，TyG 指数、甘油三酯葡萄糖－体重(Triglyceride-Glucose-Body Mass Index, TyG-BMI)指数、TG/HDL-C 以及 METS-IR 与多支血管 CAD 的风险显著相关。构建 ROC 曲线以评估 CAD 严重程度提示，METS-IR 的 AUC 值为 0.726 (95% CI 0.677~0.775)，优于 TyG 指数的 AUC 值 0.673 (95% CI 0.620~0.726)。来自泰国的一项为了了解 IR 替代标志物与泰国警察代谢综合征和高血压患病率之间的关系的研究中，关于预测高血压的能力，TyG 指数、METS-IR 的 AUC 值(分别为 0.634 到 0.638)高于传统肥胖指标如 BMI (AUC: 0.630)和腰围(Waist Circumference, WC) (AUC: 0.618) [76]。一项旨在比较 METS-IR、TG/HDL-C、TyG 指数、TyG-BMI 指数在预测 PCI 术后患者心血管预后方面的能力的回顾性研究结果提示：四种 IR 指标在女性个体中均与 MACCEs 显著相关，而在老年患者中只有 TyG-BMI 指数和 METS-IR 与 MACCEs 相关。纳入这些 IR 指标并未提高女性或老年患者基本风险模型对 MACCEs 的预测能力[77]。

另一方面，研究结果支持 TyG 指数优于 METS-IR 的如下：一项为了评估传统心脏代谢指标以及更新颖的致动脉粥样硬化指数和胰岛素抵抗替代标志物在识别 CAD 风险个体中的价值的研究表明，进行针对潜在混杂因素调整的多元回归分析后，TyG 指数水平升高使 CAD 风险显著恶化，增加近 4 倍；然而在多元回归模型中将 METS-IR 作为连续变量与 CAD 风险进行分析时，未发现显著的总体关联[78]。再一项旨在比较 TyG 指数、TG/HDL-C 以及 METS-IR 在复杂 PCI 术后患者中的预后价值的大规模的队列研究中，TyG 指数，而非 TG/HDL-C 或 METS-IR，与接受复杂 PCI 患者的 MACE 呈正相关；同时，将 TyG 指数添加到原始模型中导致 C 统计量(0.618 对 0.627)、净重新分类改善指数(Net Reclassification Improvement, NRI) (0.12)和综合判别改善指数(Integrated Discrimination Improvement, IDI) (0.14%)显著改善，而将 TG/HDL-C 或 METS-IR 添加到原始模型中未观察到显著改善；复杂 PCI 定义为具有以下至少 1 个特征：植入 3 个或更多支架、治疗 3 个或更多病变、分叉 PCI、总支架长度 60 mm 或更长、左主干 PCI 或重度钙化[79]。

最后 Mirjalili 等人[80]在对 2000 名年龄在 20 至 74 岁的个体进行了为期 9.9 年的随访后，利用多变量 Cox 比例风险模型研究了 TyG 指数、TyG-BMI、甘油三酯－葡萄糖－腰围指数(Triglyceride-Glucose-Waist Circumference, TyG-WC)、TG/HDL-C 以及 METS-IR 与 CAD 发生之间的关联，采用 ROC 来比较这些指标的预测效能及其预测 CAD 的相应临界值，以及使用三种不同的嵌入式特征选择方法：LASSO、

随机森林特征选择和 Boruta 算法以评估和比较胰岛素抵抗替代标志物在预测 CAD 中的作用时，结果显示 TyG 指数是唯一在完全调整模型中显示与 CAD 相关的胰岛素抵抗替代标志物(HR: 2.54, 95% CI: 1.34~4.81)。此外，与其他胰岛素抵抗替代指标相比，它在 ROC 曲线下面积最高(0.67 [0.63~0.7])。所有嵌入式特征选择方法都表明 TyG 指数是预测 CAD 最可靠的胰岛素抵抗替代标志物。根据随机森林的其他条件不变曲线，TyG 指数的预测能力在 9 之后随着正斜率稳定增加。

总的来说，TyG 和 METS-IR 在心血管预测中的比较结果不一致，一些研究支持 METS-IR 在 CAD 严重程度预测中的优越性，而其他则显示 TyG 在预后评估中更佳。但已有研究同样存在异质性高、样本多样性不足，且缺乏直接比较的纵向数据的缺点。需要更多头对头研究评估两者在不同人群中的相对优势。

## 4. 结论

综上所述，IR 作为代谢紊乱的核心机制，通过促进炎症反应、内皮功能障碍、氧化应激和斑块易损性等病理过程，在 CVD 的发生、进展和预后中发挥关键作用。传统胰岛素抵抗评估方法如 HEC 和 HOMA-IR 因操作复杂和成本高昂，其临床适用性受限，推动了新型非胰岛素依赖替代指标的发展。TyG 指数作为简单可靠的 IR 替代指标，已被证实与高血压、动脉硬化、ASCVD 发病风险以及 CAD 预后(如 MACE 和全因死亡)密切相关，尤其在 PCI 术后患者中显示出对 GRACE 评分的预测增量价值。METS-IR 作为另一种新兴指标，在某些研究中表现出优于 TyG 的 CAD 严重程度预测能力，但由于研究异质性和人群偏倚的存在致使两者之间的比较结果不一致。

这些发现强调新型 IR 替代指标在 CVD 风险分层和预后评估中的潜在临床价值，有助于指导个性化干预策略。根据现有证据，在资源有限的基层医疗机构，TyG 指数可作为 CVD 风险初筛的有效工具，便于基于常规生化参数快速识别高风险患者，并指导初步的生活方式干预和脂质血糖管理；而在综合性医院，可结合 METS-IR 进行更全面的代谢风险评估，以优化 CAD 严重程度和预后的判断。然而，现有的证据主要依赖观察性和荟萃分析，缺乏大型随机对照试验来确立因果关系和干预效果，且多局限于亚洲人群。未来研究应聚焦多民族纵向队列、头对头比较以及整合机器学习方法，更具体地设计前瞻性研究，评估例如以降低 TyG 指数为治疗靶点的干预策略(如基于 TyG 阈值的强化生活方式调整或他汀类药物联合降糖治疗)是否能带来心血管获益，以填补知识缺口并验证这些指标在预防 CVD 中的转化应用。

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