

## Progresses of quantitative assessment of placental microvascular flow and fetoplacental circulation of ultrasound for monitoring fetal growth restriction

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**[Abstract]** Fetal growth restriction (FGR) is one of the leading causes of perinatal mortality and long-term complications. Traditional diagnostic methods are unable to distinguish FGR from small for gestational age infants, often resulting loss of optimal intervention opportunities. Doppler hemodynamic assessment, three-dimensional power Doppler and integrated application with artificial intelligence have significantly improved the capacity for early identification and risk stratification of FGR. The progresses of quantitative assessment of placental microvascular flow and fetoplacental circulation of ultrasound for monitoring FGR were reviewed in this article.

**[Keywords]** fetal growth retardation; placenta; microcirculation; ultrasonography; artificial intelligence

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## 超声胎盘微血流定量评估及母胎血流监测 诊断胎儿生长受限进展

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**[摘要]** 胎儿生长受限(FGR)是导致围产儿死亡及远期并发症的主要因素之一;传统诊断方法难以区分 FGR 与小于胎龄儿,易错失最佳干预时机。多普勒血流动力学评估、三维能量多普勒及其与人工智能的融合应用显著提升了早期识别 FGR 及风险分层的能力。本文就超声胎盘微血流定量评估及母胎血流监测诊断 FGR 进展进行综述。

**[关键词]** 胎儿生长迟缓; 胎盘; 微循环; 超声检查; 人工智能

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胎儿生长受限(fetal growth restriction, FGR)指胎儿未达遗传生长潜能,超声估测胎儿体质量(estimated fetal weight, EFW)或腹围小于同孕龄第 10 百分位;严重 FGR 指 EFW 或腹围小于同孕龄第 3 百分位或伴血流异常,可进一步分为早发型(<32 周)与晚发型( $\geq 32$  周)<sup>[1]</sup>。FGR 可致胎儿缺氧及代谢紊乱,增加远期神经发育迟缓及代谢综合征风险,是围产

儿主要死因之一<sup>[2]</sup>;其在发达国家的发生率约 3%~9%,在部分发展中国家则可高达 25%<sup>[3]</sup>。传统超声通过测量胎儿双顶径、头围、腹围及股骨长等生物计量参数,结合公式估算 EFW 并绘制生长曲线以评估胎儿生长发育<sup>[4]</sup>,存在以下局限:仅据 EFW 难以区分 FGR 与小于胎龄儿(small for gestational age, SGA)<sup>[5]</sup>,后者指出生体质量低于同胎龄第 10 百分位

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的新生儿,多可经产后追赶生长达到正常体型、围产风险较低<sup>[6-8]</sup>,而 FGR 与死产、神经损伤等严重不良结局相关<sup>[9]</sup>;测量易受胎儿体位、设备精度及操作经验影响<sup>[10]</sup>;难以全面反映个体生长差异及潜在病理信息<sup>[11]</sup>。FGR 多于孕中晚期出现异常表现,易错失最佳干预时机<sup>[12]</sup>,临床亟需早期特异性诊断工具。本文就超声胎盘微血流定量评估及母胎血流监测诊断 FGR 进展进行综述。

## 1 多普勒血流动力学评估 FGR

以多普勒评估血流动力学是早期识别 FGR 与预测预后的核心方法之一,通过系统检测脐动脉(umbilical artery, UA)、大脑中动脉(middle cerebral artery, MCA)、静脉导管(ductus venosus, DV)及子宫动脉(uterine artery, UtA)等关键血管的血流频谱参数而全面评估胎盘-胎儿循环<sup>[13]</sup>。UA 血流频谱参数异常,如收缩期/舒张期比值(S/D)、阻力指数(resistance index, RI)或搏动指数(pulsatility index, PI)升高均直接反映胎盘灌注不足,原因可能在于胎盘绒毛血管树稀疏、血管内皮损伤及微血栓形成导致胎盘末梢循环阻力增高、引起胎儿-胎盘单位血流量减少<sup>[14-15]</sup>。MCA 是胎儿中枢神经系统代偿反应的重要窗口,胎儿缺氧触发“脑保护效应”,表现为 MCA 扩张、RI 与 PI 下降及舒张期血流速度增加。MCA-PI 值低于同孕龄均值 1.5 个标准差是诊断胎儿酸中毒的敏感指标,常早于胎心异常出现。脑胎盘率(cerebroplacental ratio, CPR)即 MCA-PI 与 UA-PI 比值,以  $CPR < 1.08$  诊断 FGR 具有较高敏感度(90%)与特异度(85%),是重要的复合评价 FGR 指标<sup>[16-17]</sup>。DV 血流频谱反映胎儿右心功能状态。DV-PI 升高或 A 波缺失/反向是预测短期胎儿死亡风险的敏感指标,对于预警早发型 FGR 尤为重要;DV-PI > 第 95 百分位提示不良预后风险显著增加,其本质原因是胎儿心脏功能失代偿及全身循环衰竭;DV S 波与 D 波改变提示胎儿右心室顺应性下降及心功能代偿障碍<sup>[18-20]</sup>。UtA 血流频谱参数反映母体-胎盘循环;随孕周增加,血流阻力逐渐降低。FGR 可致子宫螺旋动脉重塑障碍,使 UtA 血流阻力增高、舒张期血流减少<sup>[21]</sup>。国际妇产科超声学会实践指南(International Society of Ultrasound in Obstetrics and Gynecology Practice Guidelines, ISUOG)指出,对于胎龄 < 32 周且腹围或 EFW < 第 10 百分位的胎儿,  $UtA-PI > 第 95 百分位$  或存在舒张期切迹(尤其胎龄 24 周后持续存在)支持 FGR,并提示子痫前期及胎盘功能不全风险

增高<sup>[9]</sup>。但测量多普勒血流频谱参数易受胎位、母体肥胖等因素干扰,主观性强,且对于 CPR 等参数尚无统一的临界值;如何校准参考值、缺乏长期随访数据等问题均有待解决。

## 2 超声新技术用于诊断 FGR

近年来,三维能量多普勒(three dimensional power Doppler, 3D PD)、超声弹性成像(ultrasound elastography, USE)及超微血流成像(superb microvascular imaging, SMI)等超声新技术的出现,显著提升了早期识别 FGR 与风险分层能力。针对早发型 FGR,可优先以 3D PD 评估胎盘功能,结合 USE 量化评估胎盘弹性;对于晚发型 FGR 则重点以 SMI 监测胎盘微循环,结合人工智能(artificial intelligence, AI)动态预测胎儿生长,通过阶梯式联合应用,实现从宏观结构到微观灌注的多维度精准评估。

2.1 3D PD 胎盘体积减小提示母胎交换面积不足,是 FGR 的核心病理基础<sup>[22]</sup>。3D PD 可定量评估胎盘血管构筑与血流灌注特征,其中,胎盘低阻力指数(placental low resistance index, PLI) > 0.12 高度提示胎盘功能障碍;结合深度学习算法还可自动识别胎盘血流异常区域并精准测算胎盘体积(图 1),联合传统血流动力学参数构建多维评估体系以显著提升诊断 FGR 效能<sup>[23]</sup>。此外,3D PD 胎盘血管化指数、血流指数及血管化-血流指数(vascularization-flow index, VFI)可用于评估胎盘灌注状态并预测妊娠结局。FAN 等<sup>[24]</sup>发现,3D PD 联合 2D PD 对于预测晚发型 FGR 具有一定价值,其中,VFI 鉴别早发型与晚发型 FGR 的效能良好。

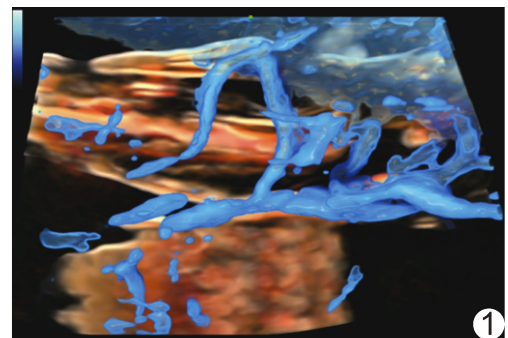


图 1 3D PD 图示孕 23 周胎盘

2.2 USE USE 通过量化胎盘硬度指数(placental stiffness index, PSI)及组织硬度评分而客观反映胎盘弹性特性。在孕晚期,正常胎盘硬度较低而 FGR 胎盘硬度显著增高;有学者<sup>[25-26]</sup>提出可将 PSI 与胎盘硬度评分视为评估 FGR 的新型超声指标。既往研究<sup>[27]</sup>发

现,USE 能在胎盘出现形态学改变之前检出其弹性变化,进而早期提示胎盘功能异常;其原理是基于组织硬度差异,通过弹性成像而实现胎盘硬度可视化,以辅助诊断胎盘功能不全(图 2)。ANSAR 等<sup>[28]</sup>报道,FGR 胎盘弹性值显著升高,且严重程度越重、弹性值越高,提示 USE 可识别胎盘局部弹性异常区域,为早期诊断 FGR 并进行分期提供了新的途径。

2.3 SMI 通过创新算法,SMI 有效抑制了组织运动伪影,显著提高了低速微血管血流的检测敏感性与空间分辨率,能无创、清晰显示胎盘绒毛间隙及螺旋动脉的微循环灌注状态<sup>[29]</sup>。与传统多普勒超声相比,SMI 可更早期、精确地识别胎盘血管树末梢的灌注缺损,直接反映胎盘功能不全的核心病理特征<sup>[30]</sup>(图 3)。

FURUYA 等<sup>[31]</sup>以 SMI 诊断 FGR 的阳性预测值达 100%, 敏感度为 89%。GARCÍA-JIMÉNEZ 等<sup>[32]</sup>发现,SMI 可显示生长受限胎儿二级和三级绒毛数量减少及 PI 降低。SUN 等<sup>[33]</sup>认为 SMI 评估胎盘微循环 PI、RI、S/D、时间平均速度和单位面积血管数量等参数的准确性均优于 CDFI。CHEN 等<sup>[34]</sup>报道 1 例孕 34<sup>+3</sup> 周 FGR 合并胎盘绒毛膜血管瘤,基于微血流灌注技术 MV-Flow<sup>TM</sup> 清晰显示 CDFI 不可见的微血管血流增加,证实高帧频滤波可进一步提高 SMI 时空分辨率、定量分析胎盘微血管指数,有望据此建立孕周特异性参考值。

### 3 AI 与自动化技术

AI 正逐步革新超声诊断 FGR 流程。利用基于深度学习的测量模型可进一步提升测量胎儿体质量、腹围等参数的精度;个体化生长预测算法通过整合多维度临床数据而实现精准风险分层;融合上述技术的全流程辅助诊断系统形成了从采集影像至临床决策的完整数字化路径,为早期识别与精准管理 FGR 提供了新的工具。SPAIRANI 等<sup>[35]</sup>基于卷积神经网络架构的开发

FGR-ResNet 模型能精准定位胎儿股骨远端骨骺、小脑蚓部等关键解剖标志点,使测量 EFW 误差率由 8.5% 降至 3.8%,显著降低了漏、误诊 FGR 风险。新型 MobileNet3Large 与 EfficientV2S 模型用于识别胎儿腹部标准切面表现优异,即便在孕妇肥胖等成像困难的条件下仍能可靠地提取胎儿腹部轮廓特征,为筛查晚发型 FGR 提供可靠依据<sup>[36]</sup>。FUNG 等<sup>[37]</sup>基于 GROW-Plus 算法、整合临床数据及超声参数构建的个体化预测胎儿生长轨迹模型能精准鉴别 FGR 与生理性生长缓慢,有助于避免不必要的医疗干预与孕妇心理负担。

### 4 小结与展望

超声技术的革新显著提升了临床早期识别 FGR 与进行风险分层的能力。通过量化胎盘灌注及胎儿循环状态,多普勒血流动力学联合 3D PD 使诊断 FGR

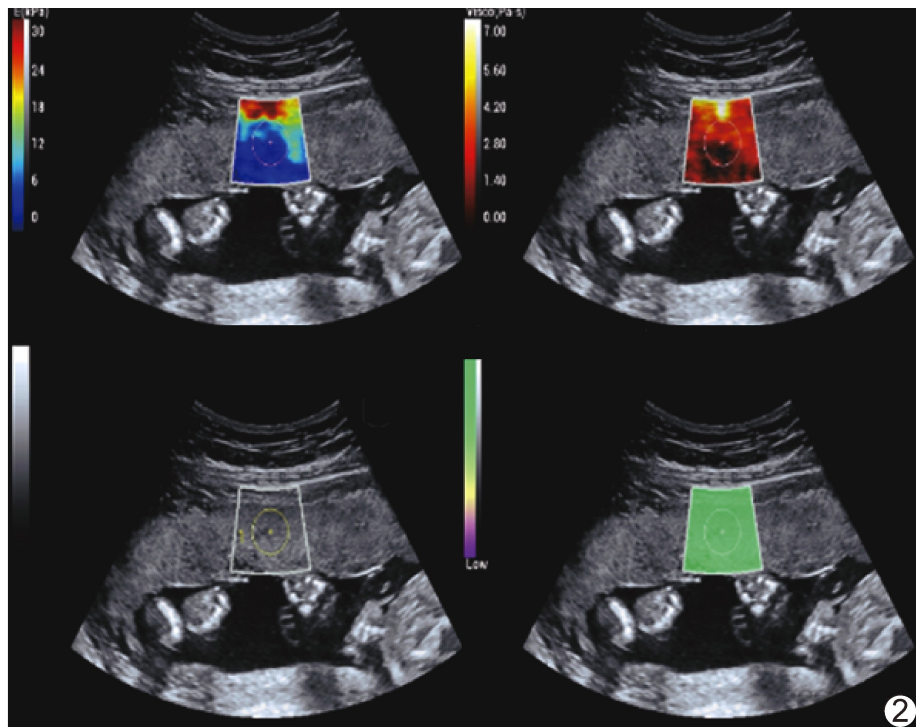


图 2 USE 图示孕 23<sup>+3</sup> 周胎盘实质硬度(硬度较高区域显示为蓝白色、较低区域呈红色)

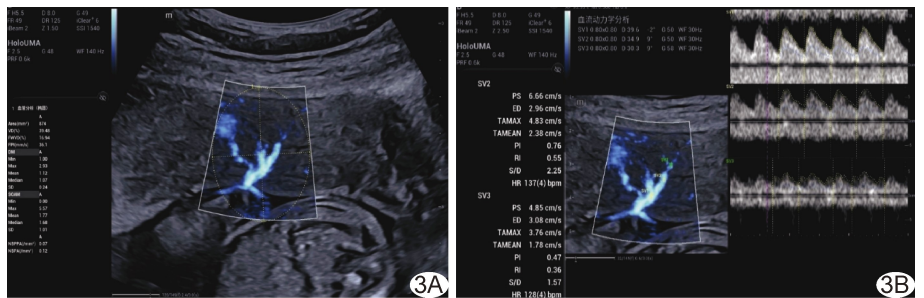


图 3 SMI 定量分析孕 23<sup>+2</sup> 周胎盘微血管走行图 A. 灌注参数和形态学参数; B. 基于多取样门频谱的多位置同步分析

敏感度提高到 85% 以上, UA-S/D 升高、MCA-PI 降低及 UtA-PI 升高均可作为诊断 FGR 提供重要依据。当前已形成融合了胎盘微血流定量评估及母胎血流监测的多功能评估体系用于诊断 FGR, 但仍面临参数校准困难、操作者依赖性高、缺失长期随访体系及验证队列规模有限等挑战。未来应构建融合高分辨率超声、胎儿 MR 与液体活检的多模态影像体系, 建立跨尺度诊断模型; 制定基于血流动力学分型的个体化干预方案(如靶向氧合支持或母体血管治疗); 开发 AI 驱动决策系统, 通过标准化参数与远程协作实现诊疗均质化。此外, 还需开展设计严谨的多中心验证, 以推动相关技术的标准化进程与临床转化应用, 最终形成从早期筛查到远期追踪的全周期管理路径, 以实现降低 FGR 围产期死亡率 30% 以上的战略目标。

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### [参考文献]

- [1] FANTASIA I, ZAMAGNI G, LEES C, et al. Current practice in the diagnosis and management of fetal growth restriction: An international survey[J]. *Acta Obstet Gynecol Scand*, 2022, 101(12):1431-1439.
- [2] DANTONIO F, KHALIL A, RIZZO G. Standardization in the definition and management of late fetal growth restriction is needed to optimize perinatal outcome[J]. *Am J Obstet Gynecol MFM*, 2022, 4(5):100597.
- [3] DAMHUIS S E, GANZEVOORT W, GORDIJN S J. Abnormal fetal growth: Small for gestational age, fetal growth restriction, large for gestational age: Definitions and epidemiology[J]. *Obstet Gynecol Clin North Am*, 2021, 48(2):267-279.
- [4] FUJITA M M, FRANCISCO R P V, RODRIGUES A S, et al. Longitudinal study of individually adjusted fetal growth[J]. *Int J Gynaecol Obstet*, 2020, 148(1):35-40.
- [5] SALOMON L J, ALFIREVIC Z, DA SILVA COSTA F, et al. ISUOG practice guidelines: Ultrasound assessment of fetal biometry and growth[J]. *Ultrasound Obstet Gynecol*, 2019, 53(6):715-723.
- [6] SAGGESE G, FANOS M, SIMI F. SGA children: Auxological and metabolic outcomes: The role of GH treatment[J]. *J Matern Fetal Neonatal Med*, 2013, 26(Suppl 2):64-67.
- [7] CHEN F, LI D Z. Born small-for-gestational age: Not just smaller[J]. *Ultrasound Obstet Gynecol*, 2023, 62(3):449-450.
- [8] CALIS P, GUNDOGDU A C, TURGUT E, et al. Do small for gestational age fetuses have placental pathologies? [J]. *Arch Gynecol Obstet*, 2024, 309(4):1305-1313.
- [9] HERTTING E, HERLING L, LINDQVIST P G, et al. Importance of antenatal identification of small for gestational age fetuses on perinatal and childhood outcomes: A register-based cohort study [J]. *Acta Obstet Gynecol Scand*, 2024, 103(1):42-50.
- [10] WRIGHT D, WRIGHT A, SMITH E, et al. Impact of biometric measurement error on identification of small- and large-for-gestational-age fetuses [J]. *Ultrasound Obstet Gynecol*, 2020, 55(2):170-176.
- [11] Society for Maternal-Fetal Medicine (SMFM), MARTINS J G, BIGGIO J R, et al. Diagnosis and management of fetal growth restriction: (Replaces clinical guideline Number 3, April 2012) [J]. *Am J Obstet Gynecol*, 2020, 223(4):B2-B17.
- [12] MUSTAFA H J, JAVINANI A, MURALIDHARAN V, et al. Diagnostic performance of 32 vs 36 weeks ultrasound in predicting late-onset fetal growth restriction and small-for-gestational-age neonates: A systematic review and meta-analysis[J]. *Am J Obstet Gynecol MFM*, 2024, 6(1):101246.
- [13] LOPIAN M, PRASAD S, SEGAL E, et al. Prediction of small-for-gestational age and fetal growth restriction at routine ultrasound examination at 35-37 weeks' gestation [J]. *Ultrasound Obstet Gynecol*, 2025, 65(6):761-770.
- [14] 中华医学会围产医学分会胎儿医学学组, 中华医学会妇产科学分会产科学组. 胎儿生长受限专家共识(2019 版) [J]. *中华围产医学杂志*, 2019, 22(6):361-380.
- [15] 罗丽萍, 李雪霞. 彩色多普勒超声联合血清学检测诊断晚发型胎儿生长受限的临床价值 [J]. *临床超声医学杂志*, 2024, 26(7):606-610.
- [16] 罗爽, 刘小丽. 彩色多普勒超声监测胎儿脑脐血流联合胎盘率诊断子痫前期孕妇发生胎儿生长受限的价值 [J]. *山西医药杂志*, 2024, 53(19):1471-1474.
- [17] 李玲, 张盼盼, 张文琴. 基于彩色多普勒超声定量参数列线图模型预测胎儿生长受限的临床价值 [J]. *临床超声医学杂志*, 2023, 25(2):90-94.
- [18] GOVENDER V, NAIDOO T D, FOOLCHAND S. The pre-eclampsia, growth restriction, and ductus venosus Doppler (GRADED) study: An observational study of early-onset fetal growth restriction and pre-eclampsia [J]. *Int J Gynaecol Obstet*, 2023, 161(1):106-113.
- [19] SEKIELSKA-DOMANOWSKA M I, MYSZKOWSKI B, CZUBA B, et al. The role of individual blood flow parameters through ductus venosus in the first and second trimesters of pregnancy in predicting the condition of the fetus and newborn [J]. *Ginekol Pol*, 2022, 93(7):558-563.
- [20] GRAUPNER O, RATH C, LECKER L, et al. Role of ductus venosus Doppler sonography for the prediction of perinatal outcome in term pregnancies complicated by gestational diabetes mellitus [J]. *Z Geburtshilfe Neonatol*, 2024, 228(4):363-369.
- [21] RIAL-CRETELO M, MARTINEZ-PORTILLA R J, CANCEMI A, et al. Added value of cerebro-placental ratio and

- uterine artery Doppler at routine third trimester screening as a predictor of SGA and FGR in non-selected pregnancies [J]. *J Matern Fetal Neonatal Med*, 2019, 32(15):2554-2560.
- [22] VEDMEDOVSKA N, REZEBERGA D, TEIBE U, et al. Placental pathology in fetal growth restriction[J]. *Eur J Obstet Gynecol Reprod Biol*, 2011, 155(1):36-40.
- [23] 朱玲, 梅丽娜, 邵冰鑫. 胎盘三维彩色能量多普勒血管超声成像在早孕期预测胎儿生长受限中的应用价值[J]. *中华全科医学*, 2024, 22(1):105-107.
- [24] FAN H, LI L, HAO C. Clinical significance of three-dimensional power Doppler combined with two-dimensional Doppler ultrasonography for evaluating fetal growth restriction[J]. *J Matern Fetal Neonatal Med*, 2024, 37(1):2322610.
- [25] 魏宇婷, 罗红. 超声弹性成像评价胎儿生长受限的研究现状[J/OL]. *中华妇幼临床医学杂志(电子版)*, 2023, 19(3):256-260.
- [26] HASEGAWA T, KUJI N, NOTAKE F, et al. Ultrasound elastography can detect placental tissue abnormalities[J]. *Radiol Oncol*, 2018, 52(2):129-135.
- [27] SPILIOPOULOS M, KUO C Y, ERANKI A, et al. Characterizing placental stiffness using ultrasound shear-wave elastography in healthy and preeclamptic pregnancies[J]. *Arch Gynecol Obstet*, 2020, 302(5):1103-1112.
- [28] ANSAR M, ALI M A, ALI N, et al. Ultrasound shear wave elastography of the placenta: A potential tool for early detection of fetal growth restriction[J]. *Clin Imaging*, 2024, 116:110329.
- [29] HASEGAWA J, SUZUKI N. SMI for imaging of placental infarction[J]. *Placenta*, 2016, 47:96-98.
- [30] FURUYA N, HASEGAWA J, HOMMA C, et al. Novel ultrasound assessment of placental pathological function using superb microvascular imaging [J]. *J Matern Fetal Neonatal Med*, 2022, 35(16):3036-3039.
- [31] FURUYA N, HASEGAWA J, DOI M, et al. Accuracy of prenatal ultrasound in evaluating placental pathology using superb microvascular imaging: A prospective observation study [J]. *Ultrasound Med Biol*, 2022, 48(1):27-34.
- [32] GARCÍA-JIMÉNEZ R, ARROYO E, BORRERO C, et al. Evaluation of placental micro-vascularization by superb microvascular imaging Doppler in cases of intra-uterine growth restriction: A first step[J]. *Ultrasound Med Biol*, 2021, 47(6):1631-1636.
- [33] SUN L, LI N, JIA L, et al. Comparison of superb microvascular imaging and conventional Doppler imaging techniques for evaluating placental microcirculation: A prospective study[J]. *Med Sci Monit*, 2020, 26:e926215.
- [34] CHEN X, WEI X, ZHAO S, et al. Characterization of placental microvascular architecture by MV-Flow imaging in normal and fetal growth-restricted pregnancies [J]. *J Ultrasound Med*, 2021, 40(8):1533-1542.
- [35] SPAIRANI E, STEYDE G, SPURI FOROTTI F, et al. Prediction of IUGR condition at birth by means of CTG recordings and a ResNet model[J]. *Comput Biol Med*, 2025, 190:110123.
- [36] CIOBANU Ș G, ENACHE I A, IOVOAICA-RĂMESCU C, et al. Automatic identification of fetal abdominal planes from ultrasound images based on deep learning[J]. *J Imaging Inform Med*, 2025, 38(6):3984-3991.
- [37] FUNG R, VILLAR J, DASHTI A, et al. Achieving accurate estimates of fetal gestational age and personalised predictions of fetal growth based on data from an international prospective cohort study: A population-based machine learning study [J]. *Lancet Digit Health*, 2020, 2(7):e368-e375.