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·综 述·

低氧对脂肪细胞发育及脂质代谢调控研究进展

刘媛，李惠侠*

南京农业大学动物科技学院，江苏 南京 210095

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摘 要：脂肪细胞的生长、分化与增殖贯穿整个生命过程，脂肪细胞中脂质代谢紊乱影响脂肪组织免疫和全身能量代谢。脂质代谢参与调控机体多种疾病的发生与发展，如高脂血症、非酒精性脂肪肝病、糖尿病和癌症等，对人和动物健康具有重大威胁。低氧诱导因子(hypoxia inducible factor, HIF)是介导机体组织器官中氧感受器的主要转录因子，HIF 可调控脂质合成、脂肪酸代谢和脂滴形成并诱导疾病发生。但由于低氧程度、时间和作用方式的不同，对机体脂肪细胞发育和脂质代谢产生有害或有益的影响还无从定论。本文总结了低氧介导转录因子的调控作用以及对脂肪细胞发育和脂质代谢调控的研究进展，旨在揭示低氧诱导脂肪细胞代谢途径变化的潜在机制。

关键词：低氧；低氧诱导因子；脂肪细胞发育；脂质代谢

Advances in regulation of hypoxia on adipocyte development and lipid metabolism

LIU Yuan, LI Huixia*

College of Animal Science and Technology, Nanjing Agricultural University, Nanjing 210095, Jiangsu, China

Abstract: The growth, differentiation and proliferation of adipose cells run through the whole life process. Dysregulation of lipid metabolism in adipose cells affects adipose tissue immunity and systemic energy metabolism. Increasingly available data suggest that lipid metabolism is involved in regulating the occurrence and development of various diseases, such as hyperlipidemia, nonalcoholic fatty liver disease, diabetes and cancer, which pose a major threat to human and animal health. Hypoxia inducible factor (HIF) is a major transcription factor

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*Corresponding author. E-mail: lihuixia@njau.edu.cn
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mediating oxygen receptors in tissues and organs. HIF can induce disease by regulating lipid synthesis, fatty acid metabolism and lipid droplet formation. However, due to the difference of hypoxia degree, time and mode of action, there is no conclusive conclusion whether it has harmful or beneficial effects on the development of adipocytes and lipid metabolism. This article summarizes the regulation of hypoxia stress mediated transcription regulators and regulation of adipocyte development and lipid metabolism, aiming to reveal the potential mechanism of hypoxia induced changes in adipocyte metabolism pathways.
Keywords: low oxygen; hypoxia inducible factor; adipocyte development; lipid metabolism

脂肪是人和动物储存能量的主要形式，也是维持生命活动的必需营养物质。脂肪组织的形成由脂肪细胞发育而来，包括脂肪细胞增殖、分化和肥大的过程。在转录因子作用下，前脂肪细胞经过增殖分化最终发育为成熟脂肪细胞，过氧化物酶增殖物激活受体(peroxisome proliferator-activated receptor, PPAR)-γ 和 CCAAT 增强子结合蛋白(CCAAT enhance-binding protein, C/EBP)α 为脂肪细胞终末分化过程中关键的转录因子，可激活一系列脂肪细胞特异性基因表达[1]。当人或动物体内因组织氧气供应不足或用氧障碍会导致缺氧，引起机体代谢、各器官功能和形态结构异常。低氧导致氧自由基生成和抗氧化保护之间失衡，生物分子氧化损伤。低氧诱导因子(hypoxia-inducible factor, HIF)是低氧应激时细胞反应的主要调控因子，也可调节脂质摄取和运输、脂肪酸代谢、甘油三酯(triglyceride, TG)合成和脂滴形成过程[2-3]。肥胖患者脂肪组织中 HIF-1α 的 mRNA 和蛋白表达均显著升高[4]，导致脂肪组织纤维化[5]。低氧诱导 *HIF-2α* 基因上调，促进肝脏脂质合成并抑制脂肪酸 β 氧化，加剧非酒精性脂肪肝病(nonalcoholic fatty liver disease, NAFLD)发生[6]。除了病理性缺氧，高海拔地区的人和动物也面临氧气不足，如高原地区牦牛虽通过进化对低氧环境产生耐受，但牛的产奶量受影响[7]。而从外地引进品种无法适应低氧环境，即使通过品种改良依旧有不同程度的脂质代谢紊乱或应激症状等，导致产奶量急剧下降。因此，无论是在医学或是畜牧业发展中，探究低氧对脂质代谢的影响刻不容缓。本文综述了低氧对脂肪细胞发育和脂质代谢调控的研究进展，以期为脂质代谢相关疾病的治疗提供理论依据。

1 脂肪细胞发育和脂质代谢

1.1 脂肪细胞的来源与分化

哺乳动物脂肪组织分为储存能量的白色脂肪组织(white adipose tissue, WAT)和释放能量的棕色脂肪组织(brown adipose tissue, BAT)，分别由白色和棕色脂肪细胞组成。WAT 大多分布于皮下和内脏，其沉积是造成动物机体肥胖的主要原因。肩胛骨间隙分布较多的 BAT，细胞中线粒体数量多，通过解偶联蛋白 1 (uncoupling protein 1, UCP1)将跨线粒体内膜的质子势能与 ATP 解偶联，将能量转化为热能，从而促进动物机体产热和能量消耗[8]。米色脂肪是 WAT 向 BAT 转变的中间产物。动物消耗体内 WAT 时，氧化代谢加速，脂肪细胞由白色变成米色，并携带产热功能。因此，促进脂肪组织产热是抑制机体肥胖的有效途径[9]。脂肪细胞起源于中胚层血管基质的多能间充质干细胞(mesenchymal stem cells, MSCs)。MSCs 能定向分化为脂肪、成骨和成肌细胞等。中胚层衍生的脂肪细胞谱系直接影响脂肪细胞发育。以往研究显示，WAT 和 BAT 细胞分别来自不同的谱系：BAT 细胞来自肌源性因子(myogenic factor, Myf5)细胞谱系，WAT 细胞则不是[10]。将敲除 Myf5-Cre 的等位基因与荧光

标记成熟脂肪细胞报告基因结合，量化 Myf5 谱系对 WAT 和 BAT 细胞的影响，发现只有一个子集的 BAT 细胞来自 Myf5-Cre 前体，而大多数小鼠背前 WAT 细胞来源于 Myf5-Cre 前体，并且脂肪细胞谱系随着动物年龄和性别不同而改变，同时证实配对盒蛋白 3 (paired box proteins 3, Pax3)-Cre 在 WAT 和 BAT 细胞中与 Myf5-Cre 谱系有很大程度的重叠[11]。然而，为揭示脂肪细胞发育起源在治疗机体肥胖并发症和改善动物体内脂质沉积中的作用，WAT 棕色化成为近年来一大研究热点，如肌肉因子 β-氨基异丁酸能诱发机体产热，促进 WAT 棕色化，降低体脂[12]。如果能掌握 WAT 向 BAT 转变的开关，是否可以有效预防和减少肥胖的发生，改善动物体内脂肪沉积，这值得探究。

WAT 和 BAT 细胞分化过程含两个阶段，前期是 MSCs 经脂肪祖细胞分化为前脂肪细胞，终末分化阶段由前脂肪细胞经过多轮有丝分裂和转录因子调控发育为成熟脂肪细胞(图 1)。分化过程中，前脂肪细胞早期形成标记物是脂肪细胞发育的关键。研究表明，骨形成蛋白 4 (bone morphogenetic protein 4, BMP4)通过抑制 DNA 甲基化促进 MSCs 向脂肪细胞谱系稳定转化[13]。前脂肪细胞系转录测序分析发现锌指蛋白 423 (zinc finger protein, *ZFP423*) mRNA 水平显著升高，并在 WAT 和 BAT 组织中富集，体内敲除实验进一步证实 *ZFP423* 为前脂肪细胞形成的调节因子，主要作用在 PPAR-γ 上游[14]。核转录因子 7 类似物 1 (transcription factor 7 like 1, TCF7L1)是脂肪细胞前体表型的主要决定因素[15]。近来证实，E3 泛素连接酶 SIAH2 和二肽基肽酶 4 (dipeptidyl peptidase 4, Dpp4$^+$)蛋白为前脂肪细胞形成的标记物[16-17]。由于前脂肪细胞标记基因直接决定了 MSCs 成脂的命运，但各标记基因间相互调控研究仍是冰山一角，故而探究脂肪细胞前体表型的决定因素有利于从根源上调控脂肪细胞发育与分化。此外，C/EBP α、C/EBP β、PPAR-γ 和类固醇调节元件结合蛋白家族(sterol regulatory element binding proteins, SREBPs)等转录因子主要作用于脂肪细胞分化的第二阶段。C/EBP α 与 PPAR-γ 共同作用介导脂肪细胞生长停滞和终末分化[18]。结合蛋白 C/EBP β 则促进小鼠前脂肪细胞 3T3-L1 的有丝分裂克隆扩增[19]。综上所述，虽然调控脂肪细胞发育靶基因的研究相对透彻，但其调控机制仍有待解析。

1.2 脂质代谢的调控

脂质代谢是维持体内脂质稳态的重要生命进程，主要包括 3 个部分，首先从食物中摄取的脂质被机体吸收，其次在肝脏中经过复杂的过程合成内源性脂质，以及各组织细胞转运胆固醇至

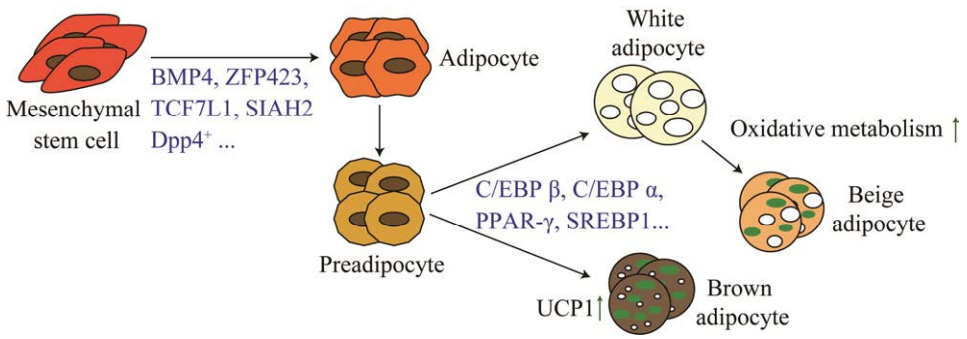

图 1 脂肪细胞分化过程

Figure 1 The process of adipocyte differentiation.

肝脏进行再调节，体内 TG 和总胆固醇水平是衡量机体脂质稳态的重要指标。脂质代谢过程涉及多种转录因子调节，如 PPAR-α、PPAR-γ、SREBP1、脂肪酸合成酶(fatty acid synthetase, FASN)和肉毒碱棕榈酰转移酶 1 (carnitine palmitoyl transferase, CPT1)等。PPAR-α 可通过调控下游靶基因 *CPT1* 控制线粒体中脂肪酸 β 氧化，而 PPAR-γ 能促进细胞 TG 合成[20]。SREBP1 是胆固醇调节元件，在脂肪酸与 TG 生物合成过程中控制脂质合成上游基因的表达，还促进 FASN 表达，增加肝脏中的脂质合成[21]。FASN 是脂肪酸链从头合成的关键代谢酶，调节机体能量代谢和平衡。此外，多种信号通路参与脂质代谢的调控：激活 PERK-eIF2α 信号通路，促进脂质合成基因表达和非酯化脂肪酸诱导的牛肝细胞脂质积累，加剧围产期奶牛脂肪肝病[22]。在慢性砷诱导的脂代谢紊乱模型中，ERK/PPAR 信号通路发挥重要作用[23]。然而，在生产上，围产期奶牛常因肝脏摄入过量脂类，引发脂肪肝，严重时奶牛尿酮浓度增加和采食量降低，影响消化功能，且常伴发其他疾病，如胎衣不下、生产瘫痪和子宫内膜炎等[24]。研究脂质代谢的发生机制除解决许多人类疾病外，也用于畜牧生产，如将动物体脂肪堆积的营养物质转移或分配到肌肉生长过程，提高肌肉组织生长速度和肉类动物的瘦肉率。相反，为提高肉质和口感，可适当增加肌内脂肪含量，如 *SIRT4* 基因可调控秦川牛的脂肪沉积，*ELOVL6* 基因调节脂质代谢和脂肪细胞增殖[25-26]。本课题组先前的研究显示，脂肪因子 *Chemerin* 可通过激活 ERK1/2 途径诱导牛肌内成熟脂肪细胞脂解[27]。因此，探究脂质代谢的调控机制除了对人和动物疾病的发生发展至关重要，还可用于改善肉品质等家畜育种实践。

2 低氧诱导的适应性反应

生理状态下，细胞需要持续氧气供应以维持生物能稳态，而高原地区氧气浓度稀薄造成机体组织缺氧，或机体发生肿瘤和肥胖时，细胞和组织中氧气供应不足会打破氧气供应和代谢需求间的平衡，造成机体氧化应激和疾病发生。低氧适应性反应的主要机制包括机体内活性氧(reactive oxygen, ROS)水平和转录因子调控。ROS 水平升高是机体缺氧的标志，缺乏分子氧会关闭线粒体电子传递链，阻止氧气还原为水并干扰 ATP 生成[28]。HIF 转录因子是协调细胞对低氧反应的重要转录因子，有广泛的靶基因谱，包括与低氧适应、炎症发展和肿瘤生长等相关的近 100 种靶基因[29]。HIF 转录因子由 α 亚基和 β 亚基组成。亚基包括 HIF-1α、HIF-2α 和 HIF-3α，其中 HIF-1α 表达普遍并参与葡萄糖代谢基因调控，而 HIF-2α 和 HIF-3α 在特定细胞内表达，如 II 型肺泡细胞、肾间质和肝实质等细胞[30]。

常氧下，HIF 转录因子的 α 亚基可被脯氨酰羟化酶(prolyl hydroxylase domains, PHD)快速羟基化，羟基化的 HIF-α 与冯希佩尔-林道(von Hippel–Lindau, pVHL)蛋白结合发生泛素化，继而被蛋白酶体降解。pVHL 肿瘤抑制因子作为 E3 泛素连接酶复合物的组成部分，在 HIF 转录因子降解中起决定作用[31]。因此，编码 pVHL、PHD 和 HIF 的 3 个基因突变都可能导致 HIF 积累。HIF-1α 亚基翻译后，除了羟基化外，还受类泛素化、乙酰化、去乙酰化和 S-亚硝基化的影响[32]。而后，缺氧诱导因子抑制因子(factor inhibiting HIF, FIH)也被证实可通过羟基化 HIF-α 天冬酰胺基残基，阻止 CREB 结合蛋白(CREB-binding protein, CBP)/p300 共激活子募集，调节 HIF 的转录活性[33]。低氧时 PHD 失活，HIF-α 停止降解并蓄积，后进入细胞核与 HIF-β

结合形成二聚体，并与其靶基因启动子或增强子区域的低氧反应元件(hypoxia responsive element, HRE)结合启动基因转录，这些基因在红细胞生成、糖酵解、血管生成和细胞分化过程中起关键作用[34]。例如：在一例先天性红细胞增多症患者体内检测到 HIF-2α 种系突变[35]；糖酵解作为介导 HIF-1 反式激活的标志物，是 HIF-1 的重要靶标，靶向 HIF-1 抑制糖酵解也成为治疗癌症的理想策略[36]；在脑损伤恢复过程中，抑制小鼠周细胞 *HIF-1* 基因表达能增加细胞存活率，提高血管的完整性[37]。研究表明，低氧状态下电子传递链会产生过量 ROS，进而抑制 PHD 表达，提高 HIF-α 的稳定性和活性[38]。激活低氧所致 HIF 转录因子，可促进脂肪生成、摄取和储存相关基因表达，加重脂肪变性[30]。将 3T3-L1 细胞暴露于低氧环境可增加 TG 积累，促进细胞内大脂滴形成[39]。体外抑制 HIF-1α 通路，可减弱低氧诱导的肾小管细胞凋亡[40]。HIF-1α 和 HIF-2α 还通过调控炎症相关基因表达，促进机体炎症的发生与发展[41-42]。总之，低氧所致 HIF 转录因子激活能调控其下游多种基因表达(图 2)。

3 低氧对脂肪细胞发育和脂质代谢的影响

3.1 低氧对脂肪细胞发育的影响

脂肪组织由脂肪细胞分化而来，肥胖个体脂肪组织中脂肪细胞体积异常扩大，常伴随细胞缺氧，进而影响脂肪细胞发育。研究表明，HIF-1α 通过调控转铁蛋白受体 1 转录促进小鼠 WAT 向米色脂肪细胞分化，决定脂肪细胞命运[43]。密度梯度离心法分离培养大鼠外周血间充质基质细胞，发现适当缺氧(5% O_2)显著增加间充质基质细胞向脂肪细胞分化的潜力并增强细胞干性[44]。与其他组织的干细胞相比，人脂肪组织来源的干细胞(adipose-derived stem cells, ADSCs)较容易分离培养，而缺氧能促进 ADSCs 向软骨分化和细胞增殖，这对治疗组织再生等疾病意义重大[45]。

然而，氧气浓度也影响脂肪细胞发育(表 1)。在极度缺氧(0.2% O_2)条件下，HIF-1α 和 C/EBP δ 显著上调，增加脂肪细胞特异性基因的启动子活性，促进骨髓间充质干细胞(bone marrow mesenchymal

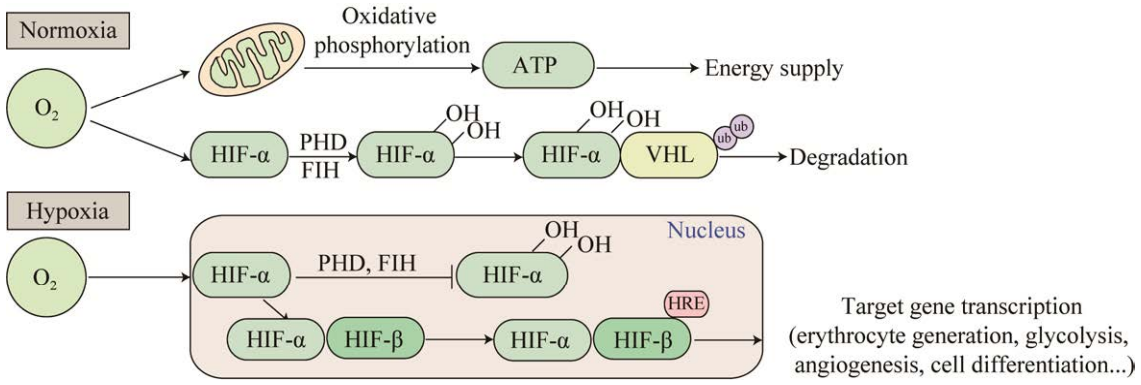

图 2 HIF 转录因子的调控

Figure 2 Regulation of HIF transcription factors.

表 1 低氧对脂肪细胞发育的影响

Table 1 Effects of hypoxia on adipocyte development

Cell type	Hypoxia/Time	Lipid metabolism gene/Protein change	Reference
BMSCs	0.2%	C/EBP δ, Leptin, LPL, CFD, PGAR and HIG2 ↑	[46]
BMSCs	10%	PPAR-γ2 and LPL↑	[47]
MSCs	1%	FASN, FABP4 and Adipsin ↓	[48]
3T3-L1	1%	PPAR-γ, C/EBP α, FATP1 and CD36↓	[49]
3T3-L1	7 d	PPAR-γ and FASN↑	[50]
	1 d	PPAR-γ and FASN-insignificant	

stem cells, BMSCs)向脂肪细胞分化[46]。与常氧相比，轻度缺氧(10% O_2)也显著促进 BMSCs 的成脂分化[47]。另一项研究表明，1% O_2 却显著抑制 MSCs 的成脂分化，减少脂滴生成[48]。在 3T3-L1 细胞中，1% O_2 显著下调 PPAR-γ、C/EBP α、CD36 和脂肪酸转运蛋白 1 (fatty acid transport protein 1, FATP1)表达，抑制细胞的成脂分化[49]。以上研究显示，轻度和极度缺氧可促进脂肪细胞分化，而其他程度缺氧抑制脂肪细胞分化，表明 O_2 浓度在脂肪细胞发育中的重要作用。除 O_2 浓度外，缺氧时间也调控脂肪细胞发育，长时间(7 d)缺氧显著抑制脂肪细胞 PPAR-γ 和 FASN 蛋白表达，短时间(1 d)缺氧脂肪生成相关指标无显著差异[50]。故低氧对脂肪细胞分化调控可能与缺氧程度、作用时间及细胞类型密切相关。但是，关于氧浓度和低氧时间对脂肪细胞发育的研究较少，且大多研究集中在人和小鼠，而地处高原地区的牛、羊等动物也面临低氧威胁，如高海拔地区奶牛牛乳中的脂肪含量偏高，但是产奶量却偏低，这也成为畜牧业发展仍需探究的实际问题。因此，探究低氧对脂肪细胞发育的影响应全方位、多角度展开。

3.2 低氧对脂质代谢的影响

脂质代谢过程包括脂肪酸的合成、降解和氧化，以及胆固醇和磷脂的代谢。正常生理条件下，脂质稳态受到严格控制，当受到遗传和环境因素干扰时，将导致脂质代谢疾病发生。低氧环境下，HIF-1α 通过激活 PPAR-γ 转录因子促进细胞外脂肪酸摄取和 TG 合成[51]。特异性敲除小鼠脂肪细胞 *HIF-1α* 基因，导致小鼠的代谢效率和呼吸交换比率降低，脂肪形成减少，并减轻机体肥胖和胰岛素抵抗，表明 HIF 转录因子在控制脂肪质量和功能方面起重要作用[52]。而另一项研究指出，血清脂蛋白也反向调节 HIF 的转录活性，这是一种全新的调节方式，具体调控机制还有待探究[53]。此外，缺氧对肿瘤微环境的影响与脂质代谢密切相关，缺氧通过代谢重编程和调节氨基酸摄取影响肿瘤生长，谷氨酰胺转运体是氨基酸的转运蛋白，缺氧的癌细胞能通过促进谷氨酰胺的摄取为三羧酸循环提供底物[54]。继而，细胞能持续产生三羧酸循环代谢物，如柠檬酸盐，随后在胞质转化为乙酰辅酶 A (acetyl-CoA)，用于合成代谢反应(如脂质合成)。最终，HIFs 诱导 FASN 和硬脂酰辅酶 A 去饱和酶表达来刺激脂肪酸合成与不饱和脂肪酸生成[55]。研究表明，HIF 通过抑制小鼠 CPT1 表达，减少脂肪酸向线粒体转运，促进细胞中脂滴累积，进而诱导肿瘤生长[56]。在人肝癌细胞中，脂肪酸结合蛋白-5

(fatty acid binding protein 5, FABP5)通过增加 *HIF-1α* 基因转录活性，促进细胞中脂质累积，加重肝癌发生[57]。干扰 HIF-1 表达会减少人乳腺癌细胞内低密度脂蛋白(low density lipoprotein, LDL)和极低密度脂蛋白(very low density lipoprotein, VLDL)摄取，抑制脂质累积[58]。然而，阴阳蛋白 1 (Yin-Yang 1, YY1)虽可通过调控 HIF-1α 发挥作用，但 YY1/PGC-1β 轴诱导的脂质代谢紊乱和肝癌病变却与 HIF-1α 无关[59]。因此，HIF-1α 对脂代谢的调控作用不是一成不变的。值得注意的是，HIF-2α 也是细胞协调缺氧重要的转录因子，但 HIF-2α 对机体调节作用研究较少。研究表明，激活 *HIF-2α* 表达能增加小鼠肝脏组织中 TG 和胆固醇含量，抑制脂肪酸 β 氧化并诱导炎症因子表达，导致肝纤维化，故认为 HIF-2α 是控制脂肪变性和脂肪性肝炎的介质[60]。缺氧诱导 HIF-2α 的过表达显著抑制脂肪酸 β 氧化和 PPAR-α 水平，促进肝脏脂肪生成，加重小鼠 NAFLD 发生[61]。进一步研究指出，HIF-2α 诱导小鼠肝细胞中的脂质积累依赖 MEK-ERK 信号通路[62]。低氧环境下，HIF-2α 也依赖围脂滴蛋白 2 (perilipin 2, PLIN2)表达调节脂质储存以维持内质网稳态，促进肾透明细胞癌[63]。在肝癌患者中，HIF-2α 可通过激活 PI3K-AKT-mTOR 信号通路传导加剧肝脏脂质累积，导致脂肪性肝癌的发展[64]。以上研究表明缺氧通过多种途径调控脂质代谢过程，但具体的调节机制仍需进一步深究(表 2)。

综上所述，多数研究认为 HIF 转录因子表达能促进脂质累积，引起脂肪变性等相关疾病发生，但也有研究指出，间歇性低氧能减轻小鼠体重，降低血糖和血胆固醇水平，缓解肝脏脂肪变性[65]。因此，低氧对脂代谢的影响可能取决于低氧的作用方式、时间、程度以及机体的生理状态等，这还有待探究。脂质代谢与人和动物机体多种疾病的发生密切相关，目前的研究主要揭示低氧对脂肪细胞发育和脂质代谢的影响，但具体调控机制的研究相对较少，需要进一步探究低氧调控脂质代谢的确切步骤。

表 2　低氧对脂质代谢的影响

Table 2　Effects of hypoxia on lipid metabolism

Cell type	Hypoxia inducible factor	Lipid metabolism gene/Protein change	Reference
Mouse cardiomyocytes	HIF-1α↑	PPAR-γ↑	[51]
Mouse model	HIF-1α↓	Serum TG, FFA and insulin resistance↓	[52]
Mouse model	HIF-1α↑	CPT1↓	[56]
HepG2 cells	HIF-1α↑	ACSL1, GPAT, LIPIN1, and DGAT2↑ CPT1A, and ATGL↓	[57]
MCF7 cells	HIF-1α↑	LDL and VLDL↑	[58]
Mouse model	HIF-2α↑	Lipid accumulation↑	[60]
Mouse model	HIF-2α↑	PPAR-α↓	[61]
Mouse primary hepatocytes	HIF-2α↑	PPAR-α↓	[62]
ccRCC cells	HIF-2α↑	PLIN2	[63]
HepG2 cells	HIF-2α↑	TG ↑	[64]

4 问题与展望

脂肪细胞发育和脂质代谢是维持机体正常生命活动的重要进程，低氧应激诱导 HIF 转录因子激活，可经多种途径调控脂质代谢相关蛋白表达并影响疾病的发生。而目前有关低氧对脂肪细胞发育和脂质代谢调控的研究仍具有一定的局限性。首先，大多数研究表明 HIF 转录因子的增加能够促进脂肪细胞特异性标志基因表达和脂质储存，但随着研究深入，发现 HIF 转录因子表达也可抑制脂质沉积、减轻病变，其上下游基因的相互调控机制有待进一步研究。其次，低氧对脂肪细胞发育和脂质代谢的调节可能取决于低氧的程度、时间及机体的生理状态，少有研究基于不同的低氧应激模式去探究其对脂肪细胞发育及脂质代谢的影响。另外，HIF 转录因子中 HIF-1α 和 HIF-2α 在脂质代谢中发挥主要作用，但其上下游基因的调节机制或两者对低氧的诱导之间如何达到一个平衡鲜有报道，需进一步开展实验或临床研究进行探讨。因此，未来的研究工作需聚焦于以下问题：不同时间和浓度的低氧对人和动物脂肪细胞发育和脂质代谢的影响；低氧对脂肪细胞发育和脂质代谢的调控机制；结合体内外实验数据将研究成果回归现实生活，进而为临床上脂质代谢相关疾病的治疗提供理论和事实依据；研究高原低氧环境下动物不同部位脂肪沉积规律及调控机制，为改善高海拔地区动物肉品质提供思路和借鉴。

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