中医药调控糖酵解重塑肿瘤免疫微环境的研究进展

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摘要：肿瘤微环境（TME）免疫抑制与糖酵解异常密切相关，肿瘤细胞通过“Warburg效应”获取代谢优势并抑制免疫应答。中医药通过多靶点调控糖酵解关键酶（如HK2、PKM2）、代谢信号通路（如PI3K/AKT/mTOR、HIF-1α）及非编码RNA，协同抑制乳酸积累、改善血管异常、解除免疫细胞代谢抑制。研究表明，中药单体和复方可增强免疫细胞浸润与功能，改善代谢微环境，并通过纳米递送系统提升治疗精准性。然而，中医药调控糖酵解-TME互作的动态机制尚未完全阐明，需借助单细胞测序等技术深入解析，并推进临床转化研究。未来应聚焦“代谢重编程-免疫激活”协同策略，为肿瘤免疫治疗提供新思路。

关键词：中医药；糖酵解；肿瘤免疫微环境；免疫逃逸；代谢重编程；免疫治疗

Traditional Chinese medicine for regulating glycolysis to remodel the tumor immune microenvironment: research progress and future prospects

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Abstract: Immune suppression in the tumor microenvironment (TME) is closely related to abnormal glycolysis. Tumor cells gain metabolic advantages and suppress immune responses through the "Warburg effect". Traditional Chinese medicine (TCM) has been shown to regulate key glycolysis enzymes (such as HK2 and PKM2), metabolic signaling pathways (such as PI3K/AKT/mTOR, HIF-1α) and non-coding RNAs at multiple targets, thus synergistically inhibiting lactate accumulation, improving vascular abnormalities, and relieving metabolic inhibition of immune cells. Studies have shown that TCM monomers and formulas can promote immune cell infiltration and functions, improve metabolic microenvironment, and with the assistance by the nano-delivery system, enhance the precision of treatment. However, the dynamic mechanism of the interaction between TCM-regulated glycolysis and TME has not been fully elucidated, for which single-cell sequencing and other technologies provide important technical support to facilitate in-depth analysis and clinical translational research. Future studies should be focused on the synergistic strategy of "metabolic reprogramming-immune activation" to provide new insights into the mechanisms of tumor immunotherapy.

Keywords: traditional Chinese medicine; glycolysis; tumor immune microenvironment; immune evasion; metabolic reprogramming; immunotherapy

肿瘤微环境（TME）是由肿瘤细胞和免疫细胞及基质细胞等组成的一个高度有序的生态系统，是肿瘤进展和耐药的核心因素，其导致的免疫抑制状态与糖酵解代谢异常密切相关[1]。相较于正常细胞，肿瘤细胞不论是在常氧或者缺氧环境中都更倾向于糖酵解作为主要能量来源，该过程也被称为“Warburg效应”[2]。糖酵解不仅促进肿瘤细胞的生长，还会通过能量底物的竞争、代谢废物的堆积及酸性微环境的形成影响免疫细胞的发育、活化及功能实现对肿瘤免疫微环境的改变，从而促进免疫逃逸[3]。而中医药具有多靶点、整体调节的优势，可以通过调控糖酵解关键酶或信号通路，改善免疫微环境，这种对肿瘤微环境整体的调控恰恰与中医药的“整体观念”不谋而合，为肿瘤治疗提供新的思路。

1 糖酵解与肿瘤免疫微环境的交互作用

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1.1 能量底物竞争

$CD8^+$T细胞活化的一个指标是从有氧磷酸化向需氧糖酵解的转变，增加的需氧糖酵解对于促进$CD8^+$T细胞增殖所需前体的合成及T细胞抗肿瘤的效应分子如IFN-γ、IL-2、IL-17和颗粒酶B的产生是必不可少的，当$CD8^+$T细胞糖酵解受到限制时就会发生功能障碍[4]；同样的，当$CD4^+$T细胞糖酵解受到限制时，其免疫监视的功能也会受到影响[5]；B细胞在肿瘤免疫中通过补体激活和抗体依赖性细胞毒作用发挥抗癌作用，但其活化仍然受限于氧化磷酸化及糖酵解[6, 7]。确保葡萄糖及氧气的供应以维持糖酵解水平对于肿瘤浸润淋巴细胞发挥抗肿瘤作用至关重要，然而，在TME中淋巴细胞在葡萄糖竞争方面处于劣势，肿瘤细胞能通过控制TME中的葡萄糖促进效应T细胞及B细胞功能障碍[4, 8]。树突状细胞（DC）通过捕获并提呈肿瘤中的抗原给T细胞来激活和控制适应性免疫，而DCs的活化、运动及迁移均需要糖酵解，当其葡萄糖受限时，其功能受到明显抑制[9]。NK细胞在受到肿瘤细胞对葡萄糖的极强调控能力的影响下，其糖酵解能力同样可能受到影响而不能发挥其抗

肿瘤作用[10]。

1.2 代谢中间产物的影响

近来研究揭示，肿瘤微环境中的代谢中间产物同样也是调控免疫应答的关键信号分子，谷氨酰胺、色氨酸等代谢物的异常分解与免疫抑制性细胞的扩增及效应T细胞的功能耗竭密切相关，其作用机制呈现显著的“双刃剑”特性。谷氨酰胺是肿瘤细胞的重要氮源，其通过谷氨酰胺酶（GLS）分解为谷氨酸和α-酮戊二酸（α-KG），后者通过三羧酸循环（TCA）为肿瘤增殖提供能量[11]。α-KG作为组蛋白去甲基化酶（如JMJD3）的辅因子，可通过降低H3K27me3水平激活免疫抑制基因（如FOXP3、IL-10）的表达，促进Treg细胞分化[12]；同时肿瘤细胞对谷氨酰胺的过度摄取导致TME中谷氨酰胺耗竭，迫使T细胞依赖低效的葡萄糖代谢，而其线粒体氧化磷酸化能力受限，最终导致IFN-γ分泌减少和增殖能力下降[13]。另有研究表明抑制肿瘤GLS活性可显著恢复$CD8^+$ T细胞的代谢适应性，并增强PD-1抗体疗效[14]。色氨酸代谢是另一关键免疫调控节点，吲哚胺2，3-双加氧酶（IDO1）在肿瘤细胞中高表达，催化色氨酸分解为犬尿氨酸（Kyn），而Kyn能激活芳烃受体（AhR）通路，触发下游STAT3/IDO1正反馈环路，促进Treg扩增并抑制$CD8^+$ T细胞活性[15]；肿瘤细胞通过耗竭局部色氨酸储备，引起TME中色氨酸的匮乏，激活GCN2/eIF2α通路诱导T细胞周期停滞和功能失能[16]。除此以外，琥珀酸通过结合GPR91受体激活NLRP3炎症小体，促进IL-1β分泌并诱导M2型巨噬细胞极化[17]。乙酰辅酶A通过增强组蛋白乙酰化（如H3K27ac）促进PD-L1基因转录，形成“代谢-表观-免疫”调控轴[18]。

1.3 乳酸介导的免疫逃逸

乳酸不仅是糖酵解的终产物，也是TME中免疫抑制的核心介质（图1）。乳酸通过降低胞内pH值、抑制丙酮酸羧化酶活性、引起NF-κB失活等抑制T细胞代谢，下调IFN-γ和颗粒酶B表达，导致$CD8^+$T细胞功能耗竭[19, 20]。对免疫细胞的单细胞测序研究进一步揭示了乳酸对肿瘤免疫微环境的重塑作用，单细胞转录组分析发现，高乳酸微环境中的Treg细胞特异性上调单羧酸转运蛋白MCT1摄取乳酸，将其转化为丙酮酸进入三羧酸循环或通过糖异生途径补充糖酵解中间产物，从而获得代谢优势，维持其免疫抑制功能[21]；此外，空间代谢组学技术通过定位肿瘤组织中乳酸的空间分布，发现其梯度变化与Treg细胞浸润区域高度重叠，为乳酸驱动的免疫抑制提供了更直观的证据，乳酸衍生的磷酸烯醇式丙酮酸通过Ca^{2+}-NFAT1信号通路上调Tregs的PD-1表达，而酸性微环境协同TGF-β进一步促进$CD4^+$T细胞向Tregs分化[22]。乳酸通过组蛋白乳酸化修饰直接上调M2型巨噬细胞特征基因的表达，促进TAMs由促炎M1型向促瘤M2型极化，促进免疫抑制因子（如IL-10、TGF-β）分泌[23]；同时乳酸通过巨噬细胞表面受体GPR81激活AMPK/LATS通路，抑制YAP入核和NF-κB活化，从而减少TNF-α等炎性因子的释放[24]。乳酸通过激活树突状细胞表面的GPR81受体，抑制MHC-Ⅱ类分子抗原呈递及钙/钙调磷酸酶信号通路，阻碍I型干扰素产生[25]；同时乳酸通过单羧酸转运体（MCTs）进入DCs后，通过负反馈抑制糖酵解并干扰TLR3/STING通路，导致抗原降解加速及交叉呈递功能受损[26]。乳酸通过抑制NK细胞NAD^+稳态、破坏穿孔素/颗粒酶表达及IFN-γ分泌、诱导线粒体应激和凋亡等多重机制削弱其抗肿瘤活性[27]。

1.4 缺氧与HIF-1α的作用

缺氧微环境中，缺氧诱导因子-1α（HIF-1α）通过双重机制驱动肿瘤免疫逃逸：其一方面通过稳定缺氧反应元件（HRE）调控代谢重编程，上调糖酵解关键酶（如HK2、LDHA）并抑制线粒体氧化磷酸化（OXPHOS），形成“Warburg效应”循环，促进乳酸分泌以维持NAD^+再生并重塑免疫抑制微环境[2, 28]；另一方面，HIF-1α直接结合PD-L1启动子区增强其转录，同时通过上调VEGF诱导血管异常化，限制T细胞浸润，并激活STAT3/IL-6或IDO1/色氨酸耗竭通路促进M2巨噬细胞极化及NK细胞功能抑制[28, 29]。在骨肉瘤中，HIF-1α通过维生素代谢酶IDO1诱导色氨酸剥夺，协同VEGF增强Treg浸润及MDSCs募集[30]。此外，单细胞测序技术也揭示了缺氧微环境中HIF-1α驱动的细胞亚群特异性响应，HIF-1α在肿瘤相关巨噬细胞（TAMs）中特异性激活糖酵解相关通路，同时HIF-1α与NF-κB形成正反馈环路，协同增强IL-10、TGF-β等免疫抑制因子分泌，而同一肿瘤样本中的$CD8^+$T细胞则表现出糖酵解抑制特征，加剧T细胞耗竭，提示HIF-1α可能通过细胞特异性代谢重编程加剧免疫逃逸[28]。临床研究证实，靶向HIF-1α可逆转免疫抑制表型，恢复PD-1/PD-L1抑制剂敏感性，提示其作为联合治疗靶点的潜力[31]。

2 中医药调控糖酵解的核心机制

2.1 靶向糖酵解关键酶的多层次干预

糖酵解关键酶（GLUT1、HK2、PKM2、LDHA等）通过调控肿瘤细胞的能量代谢和微环境酸化，在免疫逃逸中发挥核心作用，是中医药多靶点干预的重要突破口。黄芩素通过竞争性结合GLUT1的底物结合域，抑制肿瘤细胞葡萄糖摄取，还能下调mTORC2介导的GLUT1膜定位，破坏肝癌细胞葡萄糖转运效率，同时还与二甲双胍联用，通过AMPK通路增强GLUT1内化，显著提高化疗敏感性，展现了黄芩素对葡萄糖转运的双重作用[32]。山奈酚通过AKT/GSK-3β信号通路抑制HK2与线粒体

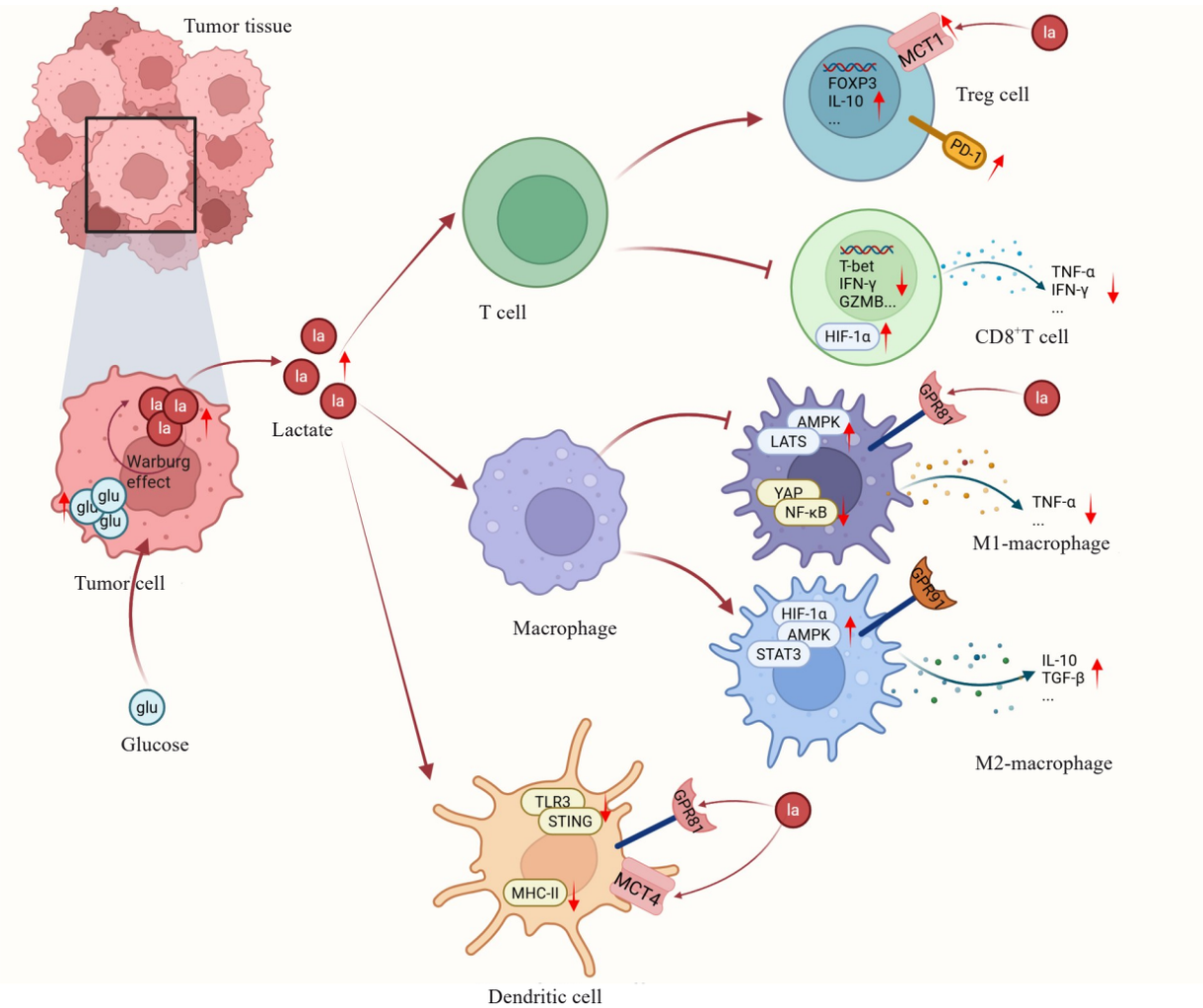

图1 乳酸重塑肿瘤免疫微环境的分子机制

Fig.1 Molecular mechanisms of lactate-induced remodeling of tumor immune microenvironment.

电压依赖性阴离子通道1(VDAC1)的结合,显著降低黑色素瘤细胞的葡萄糖消耗、乳酸生成及ATP产量,抑制肿瘤转移[33];姜黄素通过阻断HK2介导的糖酵解抑制前列腺癌细胞增殖[34];黄芩素通过抑制ALOX12依赖性铁死亡通路间接调控HK2相关代谢重编程,减轻顺铂诱导的肾损伤[35]。血根碱能结合PKM2-F26位点抑制酶活性,阻断自噬流并抑制口腔鳞癌进展[36];槲皮素通过AKT/mTOR通路下调PKM2表达,减少乳酸生成并改善免疫抑制微环境[37];白藜芦醇通过mTOR/PKM2轴抑制结直肠癌细胞糖酵解[38];木香内酯共价结合PKM2-C424位点诱导四聚体形成,抑制癌细胞能量代谢[39]。

2.2 干预代谢相关信号通路

代谢相关信号通路(如PI3K/AKT/mTOR、HIF-1α等)是连接糖酵解重编程与肿瘤免疫逃逸的关键枢纽,中医药可通过多靶点干预这些通路,逆转免疫抑制性微环境。槲皮素通过直接抑制AKT/mTOR信号轴,下调糖酵解关键酶PKM2和LDHA的表达,阻断乳酸生成[40],另外还能通过抑制mTORC1-S6K1通路,减少脂肪酸合成酶(FASN)表达,间接削弱糖酵解与脂质合成的代谢偶联,改善缺氧微环境中的免疫抑制状态[41];姜黄素通过抑制mTOR-HIF-1α轴下调PKM2表达,抑制癌细胞中的Warburg效应,降低肿瘤细胞活力[42];丹参酮通过AKT/mTOR信号通路抑制宫颈癌细胞中GLUT1、PKM2和HK2的表达,诱导细胞凋亡并抑制糖酵解[43];红景天苷通过激活脯氨酰羟化酶(PHD),促进HIF-1α泛素化降解,减少其下游靶基因VEGF、PD-L1及糖酵解酶的表达,改善缺氧微环境中的免疫抑制[44];小檗碱通过靶向IRGM1抑制PI3K/AKT/mTOR通路,减少HIF-1α介导的糖酵解酶表达[45];齐墩果酸通过抑制YAP/TAZ通路阻断HIF-1α介导的糖酵解,抑制胃癌细胞增殖[46];重楼皂苷通过稳定RORα蛋白,抑制ECM1/VEGFR2信号轴,降低卵巢癌细胞糖酵解活性及血管生成,逆转PARP抑制剂耐药性[47]。

2.3 调控非编码RNA

非编码RNA通过表观遗传调控、转录后修饰及信号通路干预,在中医药调控肿瘤糖酵解-免疫微环境互

作网络中发挥关键桥梁作用。空间转录组与代谢组联合分析发现黄芪多糖通过上调miR-138-5p靶向抑制SIRT1，阻断其去乙酰化修饰作用，抑制固醇调节元件结合蛋白1的核转位，减少脂肪酸合成酶（FASN）和乙酰辅酶A羧化酶表达，间接抑制糖酵解相关酶（如GLUT4、HK2）活性，通过空间代谢组学与非编码RNA的联合分析揭示了中医药调控糖酵解的微环境特异性[48]；木犀草素通过miR-34a靶向调控HK1表达，增强胃癌细胞对化疗药物的敏感性，抑制糖酵解依赖性增殖[49]；人参皂苷可抑制DNA甲基转移酶3A介导的DNA甲基化，上调靶向HK2的miR-603、miR-532-3p及HIF-1α的miR-519a-5p，从而抑制卵巢癌细胞Warburg效应[50]；丹参酮ⅡA通过抑制lncRNA HULC的表达，阻断其与LDHA、PKM2的相互作用，降低肝癌细胞糖酵解活性[51]；姜黄素诱导miR-34a靶向调控c-Myc，阻断其激活糖酵解基因（如GLUT1、LDHA），最终抑制结直肠癌细胞增殖及乳酸生成[52]；黄芩素通过抑制M2巨噬细胞极化相关基因（如STAT3、IL-10），减少乳酸分泌及HIF-1α介导的糖酵解，逆转肿瘤相关巨噬细胞的免疫抑制功能，增强$CD8^+$T细胞浸润[53]。

3 中医药通过糖酵解调控免疫微环境的策略

3.1 重塑免疫细胞功能

中医药通过靶向糖酵解关键酶及免疫检查点，双向调节肿瘤微环境中免疫细胞的代谢适应性与功能极化，增强抗肿瘤免疫应答并抑制免疫逃逸（图2）。

人参皂苷Rg3通过抑制HK2介导的糖酵解，降低肿瘤细胞乳酸分泌，改善肿瘤微环境酸中毒，从而增强$CD8^+$ T细胞浸润及IFN-γ分泌，逆转T细胞耗竭[54]；黄芪多糖通过miR-138-5p/SIRT1/SREBP1轴抑制脂质代谢，直接增强$CD8^+$T细胞的增殖与活化[48]；同时，黄芪多糖还通过激活STAT3/Gal-3/LAG3通路改善T细胞功能障碍，进一步支持其免疫调节作用[55]；白花蛇舌草提取物可下调高糖酵解肿瘤细胞HK2和LDHA活性，逆转其诱导的T细胞PD-1表达上调，提示其通过调控糖酵解-免疫代谢轴直接增强T细胞功能[56]；单细胞RNA-seq发现，香菇多糖能够上调PI3K/AKT/NF-κB信号通路关键蛋白，促进T细胞周期从G1期进入S期，并增加穿孔素/颗粒酶B的分泌，同时Treg细胞比例下降，提示其可能通过逆转免疫细胞代谢抑制状态增强抗肿瘤效应[57]；小檗碱处理可显著提高$CD4^+$T细胞的葡萄糖摄取率及糖酵解关键酶的表达，同时促进IL-2分泌，提示其通过激活T细胞代谢重编程增强抗肿瘤免疫应答[58]；雷公藤甲素可显著降低Treg细胞的抑制功能，同时增加效应T细胞（如$CD8^+$T细胞）的IFN-γ分泌量，提示其通过靶向Treg细胞直接重塑肿瘤免疫微环境[59]。

青蒿素通过抑制糖酵解限速酶PKM2，减缓肿瘤细胞代谢应激状态，降低乳酸积累，解除乳酸对NK细胞功能的抑制，增加其穿孔素/颗粒酶B的释放量[60]；灵芝多糖能够增强NK细胞的活性，促进其释放穿孔素和颗粒酶B[61]；丹参酮ⅡA可通过抑制HIF-1α介导的糖酵解，增强NK细胞的抗肿瘤活性[62]；苦参碱通过调控HIF-1α/STAT3通路抑制TAMs的M2型极化，下调TAMs来源的免疫抑制因子增强NK细胞的穿孔素释放量[63]。

小檗碱通过抑制STAT3/IL-10通路，减少M2型巨噬细胞极化，促进M1型巨噬细胞分泌TNF-α和IL-12，逆转免疫抑制微环境[64]；穿心莲内酯通过调控AMPK/mTOR通路，抑制M2型巨噬细胞极化，增强其促炎功能[65]；连翘酯苷能够通过阻断糖酵解关键酶HK2，减少M2型巨噬细胞的浸润[66]；苦参碱通过调控HIF-1α/STAT3通路，抑制TAMs的M2型极化[63]。

槲皮素通过AKT/mTOR通路下调Foxp3表达，抑制Treg细胞功能，减少IL-10和TGF-β分泌，解除对效应T细胞的抑制[67]；雷公藤甲素能够下调Treg细胞特异性转录因子FOXP3的表达，削弱其免疫抑制作用[68]；青蒿琥酯可通过抑制AKT信号通路，减少Treg细胞的数量和活性[69]。

木犀草素通过miR-34a靶向调控HK1，抑制髓源性抑制细胞（MDSCs）的免疫抑制功能，恢复$CD8^+$T细胞活性[70]；黄芩苷通过调控TLR4/NF-κB通路，抑制MDSCs的扩增和活性[71]。

3.2 改善代谢微环境

中医药通过多靶点干预糖酵解与其他能量物质代谢耦合网络，降低肿瘤微环境乳酸堆积及酸中毒，修复缺氧性血管结构异常，为免疫细胞浸润与功能发挥提供适宜微环境。

空间代谢成像发现，虎杖苷处理后肿瘤组织中乳酸积累区域显著减少，且与$CD8^+$T细胞浸润增加区域高度吻合[72]；川芎嗪可抑制乳酸在细胞内的积累，改善微环境代谢状态[73]。黄芪甲苷IV通过抑制VEGF表达，阻断肿瘤血管生成，抑制肿瘤增殖与侵袭转移[74]；丹参酮通过调控HIF-1α/VEGF轴，抑制血管过度增生[75]；藤黄酸通过下调HIF-1α/VEGF通路，抑制血管异常增生，恢复血管通透性，促进免疫细胞向肿瘤部位迁移[76]；丹酚酸B可通过抑制间隙连接蛋白β2，阻断肝癌细胞的糖酵解[77]。

3.3 协同化疗/免疫治疗

中医药通过“代谢重编程-免疫激活”协同机制，联合纳米递送系统增强化疗药物靶向性，逆转免疫检查点抑制剂耐药，构建代谢与免疫双重调控的抗肿瘤治疗网络。

脂质体载体依赖增强渗透滞留效应（EPR）实现肿

瘤被动靶向，并通过表面修饰实现主动靶向。负载大黄酸的脂质体通过EPR效应蓄积于肿瘤组织，增强化疗药物渗透性，抑制血管内皮细胞HK2介导的糖酵解，减少乳酸分泌，逆转肿瘤微环境酸化导致的耐药。

聚合物纳米粒通过pH响应性降解在肿瘤微环境酸性环境中释放药物，避免正常组织损伤。负载紫杉醇的靶向纳米粒通过在肿瘤微环境中pH响应性崩解，显著提高紫杉醇在肿瘤部位的浓度，抑制肿瘤组织糖酵解从而增强抗肿瘤效应，同时减少对正常组织的毒性；青蒿琥酯纳米脂质体可提高药物在肿瘤部位的富集度，增强化疗效果；穿心莲内酯纳米粒能够通过靶向递送提高药物稳定性，增强抗肿瘤活性[78]。

仿生纳米颗粒模拟细胞膜结构逃避单核吞噬细胞系统清除，并通过同源靶向识别肿瘤细胞。藤黄酸仿生纳米制剂通过表面CD47蛋白逃避巨噬细胞吞噬，延长血液循环时间，并特异性结合肿瘤细胞，靶向递送发挥血管正常化-光热作用增强临床免疫治疗[76]。

左金丸通过抑制RTKN蛋白，下调糖酵解关键酶，减少乳酸分泌，改善免疫微环境从而减少免疫逃逸[79]；黄连解毒汤能够抑制Treg细胞功能，改善免疫失调[80]；当归补血汤可改善肿瘤微环境，增强免疫细胞浸润[81]；半枝莲-白花蛇舌草药对联合PD-1抑制剂可提高抗肿瘤疗效[82]；复方苦参注射液能够作用免疫细胞重塑免疫微环境，增强索拉非尼治疗效果[83]。

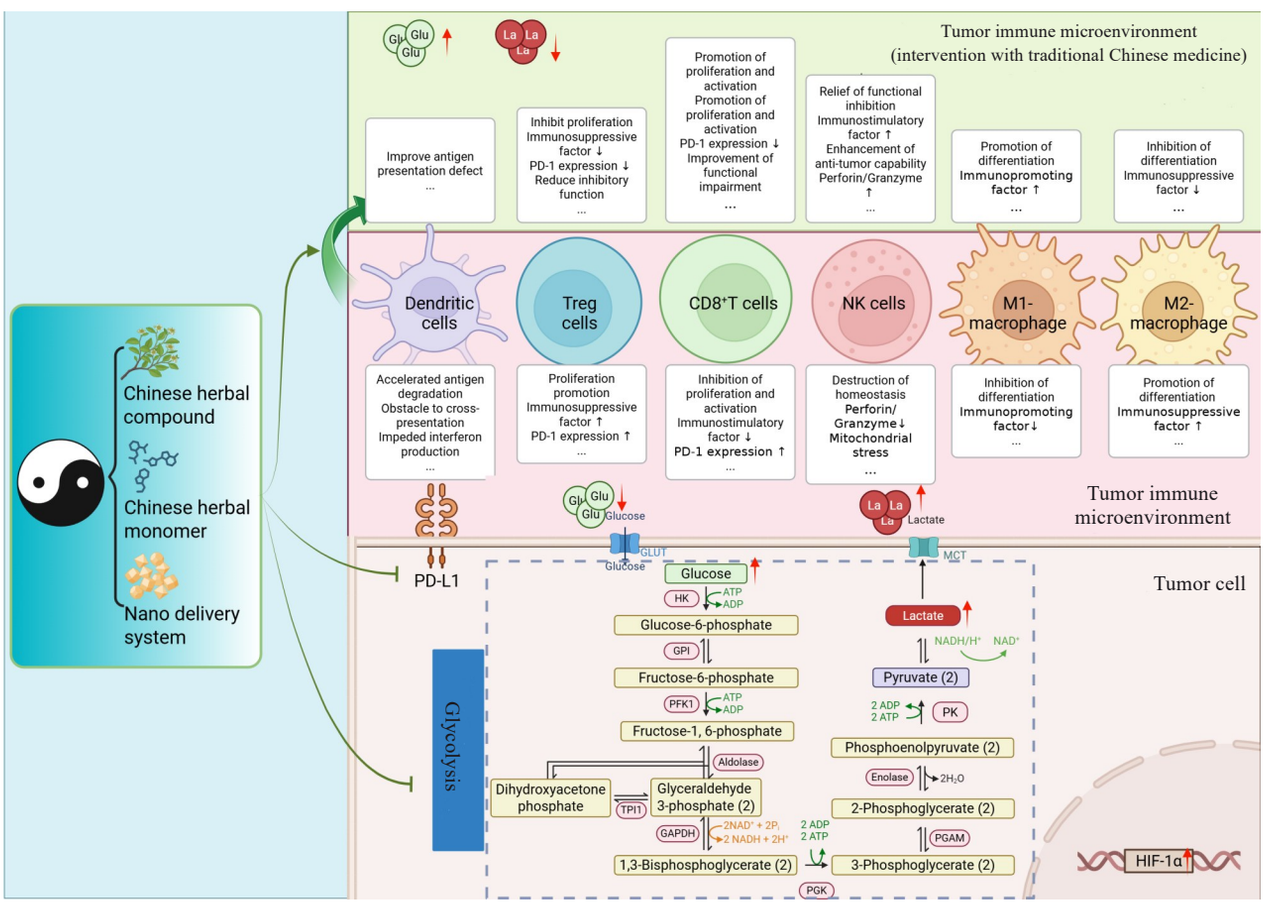

图2 糖酵解-免疫-中医药互作全景图

Fig.2 Overview of the interaction between glycolysis, immunity, and traditional Chinese medicine.

4 小结与展望

TME的免疫抑制状态与糖酵解代谢异常紧密交织，构成肿瘤恶性进展的核心驱动力。中医药凭借多靶点、整体调节的优势，通过靶向糖酵解关键酶（如HK2、PKM2）、调控代谢信号通路（如PI3K/AKT/mTOR、HIF-1α）及非编码RNA网络，在重塑免疫微环境方面展现出独特潜力。研究表明，中药单体及复方可通过抑制乳酸生成、改善缺氧性血管异常、解除免疫细胞代谢抑制等多途径，协同增强抗肿瘤免疫应答。此外，中药纳米递送系统通过靶向肿瘤代谢节点，进一步提升化疗与免疫治疗的精准性与疗效。

尽管中医药在调控糖酵解与免疫微环境方面已取得进展，但解析其动态机制仍需依赖单细胞测序、空间代谢组学等多组学技术。例如，结合单细胞RNA-seq与空间转录组可揭示中药干预后免疫细胞亚群的时空动态变化；通过空间代谢组学定位糖酵解代谢物的分

布，可直观评估中医药对微环境酸化的改善作用。中药单体可通过同时靶向糖酵解关键酶、代谢信号通路及非编码RNA发挥协同作用，这种多靶点网络增加了单一机制研究的复杂性。例如，黄芩素既可抑制HK2介导的糖酵解，又可通过调控miR-138/SIRT1轴影响脂质代谢，但其对免疫微环境的综合影响仍需借助多组学整合分析进一步阐明。复方中药通过多成分协同干预糖酵解-免疫微环境轴，但其具体配伍机制尚不清晰。例如，复方中不同成分在葡萄糖摄取、乳酸分泌等代谢节点的交互作用尚未系统解析，限制了其临床精准用药的指导价值。同时，推进中药复方与免疫检查点抑制剂的联合临床试验，建立基于代谢特征的疗效预测模型，实现临床转化验证也是刻不容缓，能够推动中医药从经验用药向精准治疗转型。另外，结合转录组、代谢组与表观遗传数据，构建“中药成分-代谢酶-免疫检查点”互作图谱，挖掘潜在协同靶点，也能为新药研发提供理论依据，实现中医药的“守正创新”。

未来需结合代谢流分析、空间代谢组学及单细胞测序技术，构建“中药成分-代谢酶-免疫细胞”三维互作模型，重点解析复方配伍的协同机制及动态调控网络，以推动中医药从经验用药向精准治疗转型。随着多学科交叉研究的深入，中医药或将为重塑肿瘤微环境、实现抗肿瘤免疫新突破开辟更广阔的前景。

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