· 临床与预防 ·

姜黄素在非小细胞肺癌三级预防策略中的机制研究

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摘要: 非小细胞肺癌是常见恶性肿瘤,发病率与死亡率飙升,虽现有多种治疗手段延长了患者生存期,但其预后仍不佳,因此规范肺癌三级预防策略极为关键。肺癌三级预防策略分为:一级病因预防,二级三早预防,三级临床预防。姜黄素因生物活性广、毒性低,成肺癌预防热点。它源于姜黄,有多种药理活性,能抑制肺癌细胞增殖、诱导凋亡、抗侵袭转移,抗肿瘤潜能显著,在肺癌三级预防中有应用潜力。本文梳理 PubMed、中国知网等数据库 2010 年 1 月—2025 年 1 月中姜黄素及其联合化疗药物的最新成果,阐述在肺癌三级预防策略中多方面作用。不过,姜黄素存在代谢快、口服生物利用度差、水溶性有限等问题,稍微阻碍其临床应用,但它仍有望成为非小细胞肺癌三级预防潜在用药或辅助手段。

关键词:姜黄素;非小细胞肺癌;三级预防;作用机制

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Mechanistic study of curcumin in the tertiary prevention strategy of non - small cell lung cancer

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Abstract: Non - small cell lung cancer is a common malignant tumor with soaring incidence and mortality rates. Although various existing treatment methods have extended the survival period of patients, the prognosis remains poor. Therefore, standardizing the Tertiary prevention strategy for lung cancer is extremely crucial. The Tertiary prevention strategy for lung cancer is divided into: primary cause prevention, secondary early prevention, and tertiary clinical prevention. Curcumin has become a hotspot in lung cancer prevention due to its broad biological activity and low toxicity. Derived from turmeric, it possesses various pharmacological activities, capable of inhibiting lung cancer cell proliferation, inducing apoptosis, and resisting invasion and metastasis, showing significant anti - tumor potential, and has application potential in the Tertiary prevention of lung cancer. This article reviews the latest achievements of curcumin and its combination with chemotherapy drugs from January 2010 to January 2025 in databases such as PubMed and CNKI, elucidating its multifaceted roles in the Tertiary prevention strategy of lung cancer. However, curcumin faces issues such as rapid metabolism, poor oral bioavailability, and limited water solubility, slightly hindering its clinical application, but it still holds promise as a potential medication or auxiliary means for theTertiary prevention of non - small cell lung cancer.

Keyword: Curcumin; Non - small cell lung cancer; Tertiary prevention; Mechanisms of action

1　引　言

肺癌乃是当下极为常见的恶性肿瘤之一,其临床发病率与死亡率均处于较高水平。近期研究显示,肺癌的发病年龄呈现出下降的趋势,与此同时,其发病率和死亡率却依旧持续攀升[1]。非小细胞肺癌约占肺癌病例的 85%,是中国癌症相关死亡的主要原因之一[2]。为了有效降低非小细胞肺癌的发病率和改善患者的预后,三级预防策略显得尤为重要。

一级预防旨在降低非小细胞肺癌的发病风险,核心措施是戒烟,因为吸烟是其主要风险因素。此外,减少环境污染和职业暴露也是重要手段。研究表明,饮食干预和植物次生代谢物可能在癌症预防中发挥

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重要作用[3]。二级预防侧重于早期检测和诊断。肺癌早期症状隐匿,常导致诊断延误[4],因此早期筛查至关重要,可提高早期肺癌诊出率和生存率。目前,低剂量计算机断层扫描联合肿瘤标志物的检测,对肺癌的早期筛查具有较大价值[5]。三级预防则关注于已确诊患者的治疗和复发预防。肺癌的治疗方案丰富多样,涵盖了手术、放疗、全身治疗、介入放射学以及姑息治疗等[6]。对于早期非小细胞肺癌患者,手术切除是主要的治疗手段,而术后辅助化疗可以提高生存率[7]。就目前而言,化疗仍然是非小细胞肺癌治疗的主要手段[8],但仍存在毒副作用,水溶性较低、血浆清除速度较快等问题,很大程度上限制了其在临床应用中的效果。尽管肺癌的三级预防得到持续改善,但非小细胞肺癌的 5 年总生存期仍然不理想,特别是对于晚期患者[9]。

近年来,传统化疗辅以草药治疗的方式逐渐兴起并日益受到欢迎,能够减轻化疗毒副作用,维持治疗效果。传统医学与替代医学对药用植物以及天然活性化合物的临床前和临床研究走向有着极为重大的影响[10]。研究表明,众多天然化合物如葛根素、槲皮素、紫杉醇、长春新碱等均展现出了抑制肺癌生长的特性[11]。姜黄素是从姜黄根茎中提取得到的一种二酮类化合物,具备抗炎、抗癌、抗氧化等多种药理特性[12],但存在水溶性差、化学性质不稳定、生物利用度低等问题,临床应用仍然受到一定程度的限制[13],所以,探寻新的防治方法与干预靶点已然迫在眉睫。本文将针对姜黄素在非小细胞肺癌三级预防策略中所发挥的作用展开综述,通过 PubMed, Web of Science, EMBASE, MEDLINE, Cochrane Library,中国知网数据库检索,初步获得 225 篇文献。去除重复文献后,剩余 188 篇。通过标题和摘要筛选,排除不符合纳入标准的 108 篇,剩余 80 篇进行全文筛选,最终纳入 80 篇文献进行分析。纳入标准包括:(1) 发表于 2010 年至 2025 年;(2) 研究对象为肺癌、姜黄素;(3) 文章语言为英文或中文。排除标准包括:(1) 非同行评议的文章;(2) 研究对象为其他肿瘤;(3) 研究设计为案例报告等非正刊文章或中科院高预警等级期刊的文章;(4) 数据不完整或无法获取全文。主要排除原因为研究对象不符(80 篇)。本研究通过整合现有的知识体系并找出其中的研究空白,为以姜黄素为基础的防治方案提供助力,改善患者生活质量。

2 姜黄素的化学结构和性质

全球有着超过 35 000 种植物,涵盖了各类香料与草药,因治疗效果佳且副作用较小被人们广泛地应用。姜黄属于姜科植物,在烹饪与药用方面均有着广泛的运用。据《本草纲目》所记载,姜黄有着颇高的药用价值,例如抵抗肝损伤、降低血压、调节血脂以及缓解痛经等等。姜黄的主要成分姜黄素是一种疏水性多酚二丙基甲烷。它在 1815 年由 Vogel 和 Pelletier 首次从姜黄里分离出来,其化学式为 $C_{21}H_{20}O_{6}$[14]。姜黄中含有 3% 至 6% 的姜黄素,是一种比较罕见的二酮化合物[15]。姜黄素在室温环境下呈现为橙色晶体,味略苦,不溶于水与乙醚,可溶于乙醇、二甲亚砜、丙二醇、冰醋酸以及碱性溶液[16]。

近十年来,姜黄素的药理活性及作用机制已引起广泛关注,其具有抗氧化、抗肿瘤和抗炎[17]等多种药理特性。研究发现,姜黄素能应用于治疗糖尿病、骨质疏松症、老年痴呆症、帕金森病、多囊卵巢综合症以及癌症等疾病。姜黄素在多方面所展现出的治疗潜力,极为显著地凸显出了它在医学领域的重要地位,推动着临床应用的深入研究[18]。

3 姜黄素对非小细胞肺癌一级预防的作用机制

非小细胞肺癌的一级预防是在疾病尚未发生时,针对病因和危险因素采取措施,以降低发病风险。Hayakawa 等人[19]发现,姜黄素有可能借助多种机制来强化免疫功能。其中一种机制是在癌细胞内部增强肿瘤抗原特异性 T 细胞的诱导。这一情况意味着姜黄素能够在刺激免疫系统更为有效地识别并靶向癌细胞方面发挥效能,而这恰恰是免疫疗法治疗癌症的一个关键要点。通过这种对免疫反应的调节方式,姜黄素能够促进人体针对癌症的自然防御能力,进而降低非小细胞肺癌的发病率。

4 姜黄素对非小细胞肺癌二级预防的作用机制

非小细胞肺癌二级预防强调“三早”,即早发现、早诊断、早治疗,是针对肺癌发生后的早期预防措施,重点通过筛查和监测手段,实现早期发现、诊断和治疗,以提高肺癌的治愈率和生存率。肺癌相关自身抗体、人工智能等也逐渐被应用于临床肺癌的筛查与早期诊断[20]。在早期 NSCLC 患者中,一组细胞凋亡/存活基因的启动子甲基化状态与 TNM 分期和总生存期降低有关[21]。虽然高甲基化 DNA 通常会沉默抑癌基因,但低甲基化或 DNA 去甲基化会促进肺癌的发生,DNA 低甲基化激活驱动恶性细胞生长的原癌基因[22]。在肺癌的发生过程中,DNA 低甲基化与高甲基化在途径中存在相互作用,DNA 低甲基化通常发生在肺癌的早期阶段,随后可导致高甲基化的发生[23]。Dini 等[24]认为,不同浓度的姜黄素可通过抑制主要为 DNMT1 甲基转移酶活性,促进 TFPI - 2 基因的表达,逆转 TFPI - 2 基因的 DNA 甲基化,该基因

甲基化状态能反映姜黄素对肺癌细胞的去甲基化作用。

5　姜黄素对非小细胞肺癌三级预防的作用机制

非小细胞肺癌三级预防聚焦临床治疗以及术后康复,旨在改善患者生活质量、延长生存期并防止复发转移。Shelash 等[25]研究表明,姜黄素能调节癌细胞增殖、侵袭、转移及血管生成等特征,抑制多种癌症类型。基因本体分析显示,姜黄素对细胞增殖、分化、氧化应激反应、细胞因子受体结合等细胞进程有广泛影响。在《京都基因组百科全书》所涉及的与肺癌相关的通路当中,姜黄素通过作用于细胞周期、NF - κB、MAPK、Th17 细胞分化等信号通路调节药物敏感性,展现抗癌活性,凸显其治疗非小细胞肺癌的潜力[26]。

5.1　*姜黄素对肺癌细胞自噬和凋亡的影响*　细胞死亡分为细胞坏死以及程序性死亡,细胞凋亡和自噬性死亡是程序性死亡的典型代表,且二者是抑制肿瘤发展的重要途径[27]。自噬对癌症的影响因环境和癌症阶段而异,在肿瘤早晚期发挥动态作用[28]。如表 1 所示,诸多研究表明姜黄素是理想的辅助药物,可调节不同机制促进非小细胞肺癌细胞的自噬和凋亡,且具备抑制肺癌细胞增长、转移、侵袭的作用,展现出作为抗非小细胞肺癌辅助药物的潜力,为后续研究提供新靶点和研发方向。

表 1　姜黄素对非小细胞肺癌细胞自噬和凋亡的影响

Table 1　Effects of curcumin on autophagy and apoptosis of non - small cell lung cancer cells

细胞类型	作用机理	结果	参考文献
A549	AMPK ↑	抑制细胞生长克服细胞对 EGFR - TKIs 耐药性	[29]
A549	miR - 192 - 5p ↑ PI3K/Akt ↓	抑制细胞增殖诱导细胞凋亡	[30]
A549	ROS ↓ SOD、CAT ↑ Akt/GSK3β ↑	通过溶酶体预防线粒体功能障碍抑制细胞凋亡	[31][32]
A549	14 - 3 - 3 ↓ Bad ↑	促进向线粒体转位诱导细胞凋亡	[33]
A549	PI3K/AKT/mTOR ↓ PI3K/AKT/PKC ↓	促进细胞凋亡和自噬	[34][35]
A549	Bcl - 2、Bcl - xl ↓ Bax ↑	促进线粒体膜电位的丧失加速细胞凋亡	[36]
A549/H1299	ACSL4 ↑ SLC7A11、GPX4 ↓	诱导细胞发生铁死亡抑制细胞生长促进细胞死亡	[37]
A549/H1299	EGFR、PI3K、P - AKT/AKT ↓ Caspase - 3、PARP ↑	抑制细胞异常增殖和迁移诱导细胞凋亡	[38]

5.2　*姜黄素对肺癌增殖、侵袭和转移的影响*　如图 1 所示,姜黄素可以通过调节细胞中某些关键信号通路的表达,抑制非小细胞肺癌细胞的存活,来抑制肿瘤细胞的增殖、侵袭和转移。De 等[39]研究结果显示,姜黄素对肿瘤细胞增殖的作用明显,在体内外均可进行抑制。Smagurauskaite 等人[40]的研究表明,在 0.25 至 5 μmol/L 的剂量范围内,姜黄素能明显抑制天然耐药性和化疗耐药性非小细胞肺癌的侵袭和转移。Wu 等[41]研究发现姜黄素可抑制非小细胞肺癌中升高的 CircRUNX1 的表达,减少肺癌细胞转移,减少肺癌细胞增殖,是肺癌发展的抑制剂。Xu 等[42]研究显示姜黄素可以通过抑制 ITGB1/miR - 384/circ - PRKCA 通路,抑制非小细胞肺癌细胞存活、集落形成、迁移、侵袭和加速凋亡来预防非小细胞肺癌细胞的恶性肿瘤。在非小细胞肺癌组织和细胞中,Circ - PRKCA 和 ITGB1 的表达增加,而 miR - 384 表现出相反的趋势。姜黄素治疗后,非小细胞肺癌细胞中 ITGB1、miR384 和 circ - PRKCA 的表达趋势被逆转,并且在 circ - PRKCA 敲低后,姜黄素对异种移植肿瘤的抑制作用显著放大。Liu 等[43]研究表明 miR - 98 作为一种肿瘤抑制因子,可被姜黄素调控,抑制多种肿瘤细胞的转移。miR - 98 的过表达通过靶向 LIN28A 抑制 MMP2 和 MMP9,从而抑制人肺肿瘤细胞的异常增殖。Nurcahyanti 等[44]在对肺癌的研究中提出,姜黄素通过调控 PI3K/AKT 通路水平,抑制 MMP - 9 和 E - cadherin 的表达,逆转辐射诱导的 EMT,降低癌细胞的迁移能力。Dong 等[45]发现姜黄素通过下调 MMP - 9、vimentin、N - cadherin 的表达来减缓 EMT 的发生,提高耐 gem 非小细胞肺癌的敏感性,降低迁移和侵袭能力。Zhang 等[46]研究表明姜黄素可以通过限制 JAK2/STAT3 信号通路抑制肿瘤球的形成,并通过介导 TLR4/MyD88 - EGFR 通路降低 AP - 1 蛋白的表达和抑制 EMT 过程从而抑制非小细胞肺癌细胞增殖和迁移。Malik 等[47]提出在非小细胞肺癌中,姜黄素通过转移 MTA1 蛋白介导的 Wnt/β - catenin 通路失活抑制细胞增殖和侵袭。Wang 等[48]发现姜黄素可以抑制 ROS、β - catenin、p - GSK3β、cyclinD1 和 c - Myc 的表达和上调 SOD 和 γ - GCS,通过氧化应激介导的 Wnt/β - Catenin 途径抑制非小细胞肺癌增殖。Li 等[49]研究提出姜黄素能通过 VEGF 信号通路介导的血管生成调控,下调 Notch 和 HIF - 1αmRNA 的水平,抑制 VEGF 和 NF - κB 的表达,降低肿瘤的重量和大小。

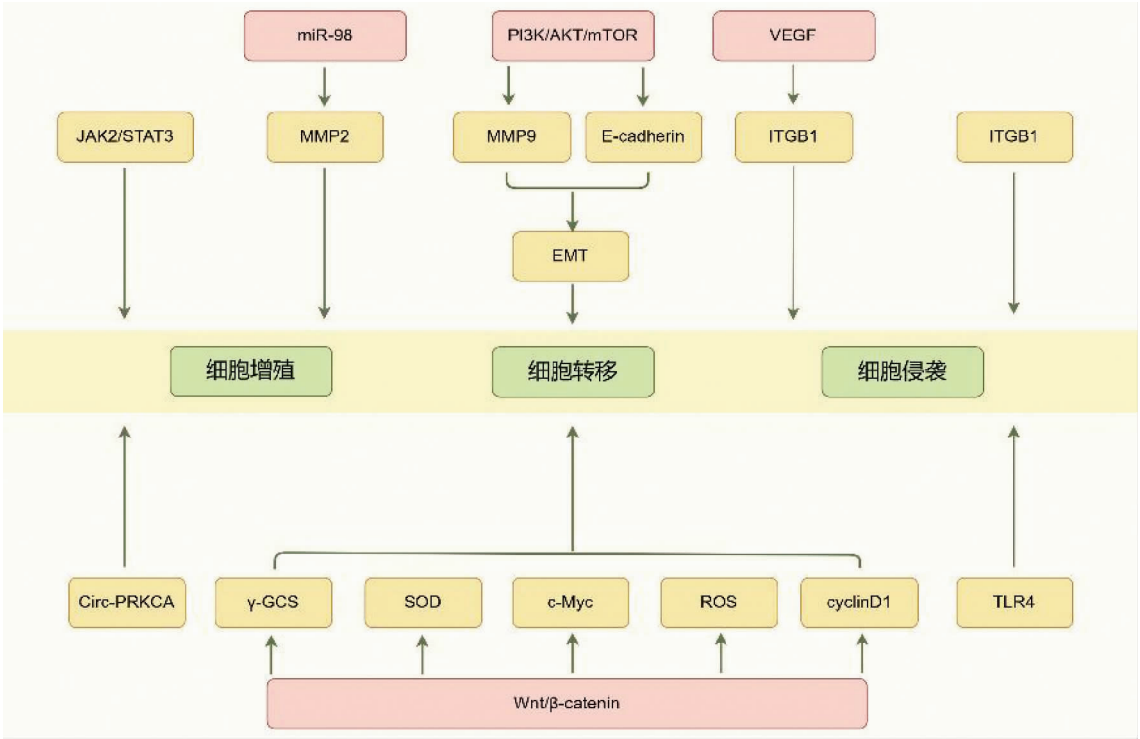

图 1 姜黄素控制抗非小细胞肺癌细胞的增殖、转移和侵袭水平。姜黄素通过调节细胞中关键信号通路的表达,抑制肺癌细胞的存活,从而抑制肿瘤细胞的增殖、侵袭和转移

Fig. 1 Curcumin controls the levels of proliferation, metastasis, and invasion in non - small cell lung cancer cells. By regulating the expression of key signaling pathways in cells, curcumin inhibits the survival of lung cancer cells, thereby suppressing tumor cell proliferation, invasion, and metastasis

5.3 *姜黄素对非小细胞肺癌表观遗传学的作用机制* 许多疾病(包括癌症)的发生和发展与表观遗传改变的失调密切相关。染色质结构显著改变可能推动癌症扩散,多种表观遗传学改变涉及这一过程。表观遗传生物标志物有助于癌症早期检测与病因确定,癌性表观遗传基因组及相关蛋白质可作为治疗靶点[50]。肺癌分子来源多样且复杂,其诊断、预后和治疗受分子异常(遗传、表观遗传、蛋白质表达等层面)研究进展的影响。如图 2 所示,在肺恶性肿瘤发生的多步骤过程中,出现多种遗传和表观遗传变化[51]。

许多研究发现,与相应的正常肺组织相比,肺肿瘤中的微小核糖核酸(microRNA,miRNA)表达异常,表明 miRNA 可能在肺癌的发生中发挥作用。MiRNA 作为非编码的短 RNA 分子,被认为是肺癌潜在的诊断、治疗和预后因子[52]。越来越多的证据表明,姜黄素对非小细胞肺癌的治疗益处通常通过控制 miRNA 的表达来介导[53]。Chae 等[54]研究表明 miRNA - 195 和 miRNA - 497 可以通过上调 TGF - β 来破坏肺癌的进展和集落形成。Zhang 等[55]发现肺癌细胞生长和迁移增强时可诱导化疗耐药,miRNA - 27b 通过下调 Snail 抑制 EMT,逆转化疗耐药。Zhan 等[56]通过构建与非小细胞肺癌 A549 细胞中姜黄素的转移抑制相关的 miRNA 基因网络,认为 miR - 330 - 5p、let - 7a - 3p、miR - 499a - 5p、miR - 1262、miR - 1276 和 miR - 331 - 5p 是关键的 microRNA 调节剂,并且通过通路分析发现,MAPK、TGF - β 和 Wnt 信号通路均呈明显下降趋势。Pan 等[57]提出姜黄素能通过靶向 c - Myc 和抑制 Wnt/βcatenin 通路上调 miR - 192 - 5p 的表达,从而限制非小细胞肺癌的生长、迁移和侵袭,沉默 miR192 - 5p 可以逆转姜黄素的抑制活性。大量研究表明 miRNA 的异常表达对肿瘤发生影响重大,提示姜黄素的抗肿瘤作用与 miRNA 有关,通过操纵关键 miRNA 的水平参与非小细胞肺癌治疗的多个重要环节。

长链非编码核糖核酸(long non - coding RNA, lncRNA)是一类长度大于 200 个核苷酸的 RNA。尽管缺乏蛋白编码能力,但在细胞增殖、迁移、药物敏感性或耐药性等多种生物学过程中发挥重要作用,其致癌或抑癌作用已在多种癌症类型中被揭示[58]。姜黄素可显著下调 PC9 亲本细胞中 lncRNA MALAT1、LSINCT5、HOTAIR 及 H19 的表达,提示其可能对其具有广谱转录调控作用[59]。

5.4 *姜黄素与其他疗法协同治疗非小细胞肺癌的效果* 目前,各种联合化疗药物可产生生化协同效应,

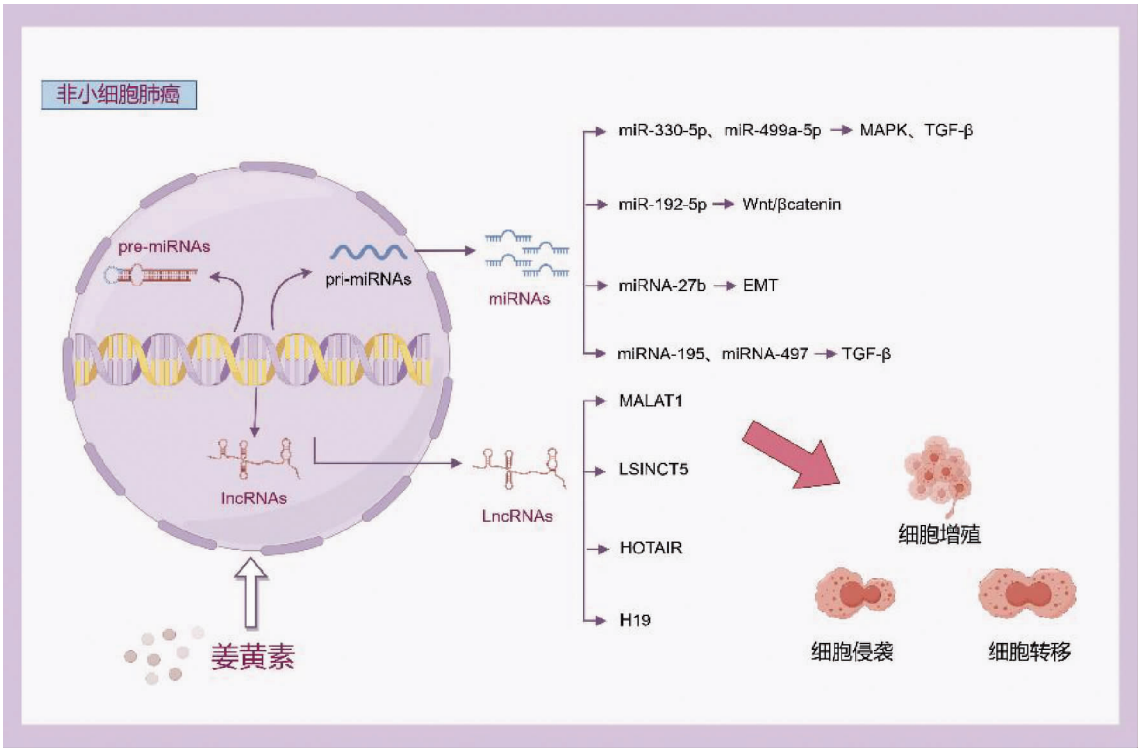

图 2　姜黄素控制抗非小细胞肺癌表观遗传学水平。大量 miRNA 在肿瘤细胞中异常表达，姜黄素通过操纵某些关键 miRNA 来调控不同的通路以及多种肿瘤相关 lncRNA 的转录调控，从而达到防治非小细胞肺癌的目的

Fig. 2　Curcumin modulates the epigenetic level in non – small cell lung cancer. Numerous miRNAs are abnormally expressed in tumor cells. Curcumin regulates different pathways and the transcriptional regulation of various tumor – related lncRNAs by manipulating certain key miRNAs, thereby achieving the goal of preventing and treating non – small cell lung cancer

抑制肿瘤细胞生长，纠正多重耐药问题，减少副作用，延长患者生存期[60]，是应对肺癌临床挑战的有力策略。如表 2 所示，姜黄素可作为辅助药物与部分化疗药物或其他抗癌药物联合使用，以克服肿瘤化疗的诸多难题。

许多化疗药物目前被用于治疗肺癌，铂类化疗是大多数晚期非小细胞肺癌患者的标准治疗方法[61]，目前临床常用铂类化合物是顺铂和卡铂。姜黄素与铂协同治疗，既能缓解铂的不良反应，又能抑制癌细胞侵袭与迁移。Hong 等人[62]采用分层技术制备顺铂和姜黄素共层封装纳米颗粒联合治疗肺癌，实验结果表明，该药物的高摄取率和显著的肿瘤抑制作用有望成为协同治疗肺癌的新方法。与其同时，研究人员已经能够通过改变治疗策略和应用新技术来创造小分子化合物来提高化疗药物的疗效，以减轻患者所服用的药物的不良反应，并延长他们的生存期。研究表明，姜黄素在恶性肿瘤中可作为化学增敏剂和放射增敏剂，与化疗药物联合使用可增强其抗肿瘤能力。

表 2　姜黄素和一些小分子化合物对非小细胞肺癌的结合

Table 2　Binding of curcumin and some small molecule compounds tonon – small cell lung cancer

姜黄素 + 无机化疗药物				
项目	细胞类型	机制	结果	参考文献
姜黄素 + 顺铂	A549	P – gp ↓ AKT/ERK ↓	促进细胞凋亡抑制迁移和侵袭提高细胞对顺铂的敏感性	[63]
姜黄素 + 卡铂	A549	AKT – IKKα 轴 ↓ NF – κB、ERK1/2 ↓	促进细胞凋亡	[64]
姜黄素 + 有机化疗药物				
项目	细胞类型	机制	结果	参考文献
姜黄素 + 紫杉醇	A549	miR – 30c – 5p ↑ MTA1 ↓	增加紫杉醇耐药细胞的紫杉醇敏感性	[65]
姜黄素 + 吉西他滨	A549/GEM	lncRNA MEG3 ↑ p53 ↑	提高细胞系多重耐药敏感性减少细胞迁移和入侵	[66]
姜黄素 + 甲氨蝶呤	A549	P – gp ↓	降低 Calu – 3 细胞活力	[67]
姜黄素 + 靶向药物				

（续表）

项目	细胞类型	机制	结果	参考文献
姜黄素 + 吉非替尼	H157/H1299	Sp1、EGFR ↓ ERK/MEK ↓	阻断 Sp1 和 HADC1 相互作用克服对吉非替尼的耐药性增强 EGFR – TKI 的疗效	[68]
姜黄素 + 克唑替尼	A549	miR – 142 – 5p ↑	增加克唑替尼的细胞毒性诱导肿瘤细胞凋亡	[69]
姜黄素 + 厄洛替尼	A549	EGFR ↓	增加厄洛替尼耐药细胞敏感性介导厄洛替尼耐药细胞凋亡	[70]

6 临床试验

目前，已有多项临床试验（如 NCT02439385、NCT01948661、NCT02138955）对姜黄素及其纳米制剂在预防和治疗癌症等人类疾病的有效性、药代动力学及安全性展开研究，针对人类多种恶性肿瘤，姜黄素相关的七项临床试验也已完成[71]。实践证明，无论是单独使用还是与其他药物联用，姜黄素在保证安全性的同时，也能发挥治疗效果，其已成为多种人类疾病多项临床试验的研究对象[72]。不过，经检索多个临床研究网站发现，当前尚无针对姜黄素治疗非小细胞肺癌的研究。若要明确姜黄素对非小细胞肺癌的疗效，还需开展更多纳入肺癌患者的临床试验。

7 结 论

非小细胞肺癌发病隐匿，多数患者确诊时已处于中晚期，生存率低，调整风险因素与筛查对提升患者生存率极为关键[73]，因此，借助三级预防策略预防肺癌发生、实现早期诊断及降低复发转移率意义重大。过去几十年，中药凭借安全、副作用小等特性，在临床实践中愈发重要。但因成分、靶点间相互作用复杂，揭示其防治疾病的潜在分子机制仍是巨大挑战[74]。天然中草药在肿瘤防治中具有很高的应用价值。天然中草药在肿瘤防治方面价值颇高，有研究表明白花蛇舌草、蛇床子等中草药及提取物，可通过提高免疫力等方式延长非小细胞肺癌患者生存期，探索天然中草药治疗该疾病意义非凡[75]。体外实验显示，姜黄素通过调节 Wnt/β – catenin、PI3K/Akt/mTOR、STAT3 等多种信号通路发挥抗癌作用[76]。其机制或许涉及阻断癌细胞增殖、促进凋亡、加速自噬死亡[77]、提高癌细胞对药物的敏感性，像抑制 PI3K/Akt 信号通路、调控关键 miRNAs 表达等。而且，姜黄素与其他药物联用能增强对非小细胞肺癌细胞的毒性。这些表明，姜黄素可能通过多靶点、多通路抗癌。不过，将姜黄素用作临床抗肺癌药物前，仍需大量临床研究。一来，相关临床试验较少；二来，其生物利用度低、水溶性差、在血液循环中不稳定、代谢快等问题限制了临床应用。开发合适给药系统提高其生物利用度，是潜在的抗非小细胞肺癌治疗手段[78]。例如，预先制备了包裹 pH 值敏感聚合物的胶束 C – NPs，以构建 pH 值响应型纳米给药系统[79]。通过纳米技术和新型药物递送系统，如姜黄素负载的纳米乳剂和聚乳酸 – 羟基乙酸（PLGA）纳米颗粒，包裹在壳聚糖纳米颗粒中的姜黄素显示出更好的细胞摄取和延长组织滞留时间，可以显著提高生物利用度和预防效果[80]。总体而言，姜黄素在肺癌三级预防策略中潜力广泛。通过改善生物利用度，与其他疗法联用，有望成为有效的肺癌辅助治疗剂，为患者提供更好的治疗选择与预后。

利益冲突声明 本研究不存在任何利益冲突

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