

孤独症谱系障碍儿童的动态发育轨迹与 基于神经可塑性和环境敏感期的精准干预

文静

贵阳市妇幼保健院, 贵州 贵阳 550003

摘要: 孤独症谱系障碍(ASD)是一种复杂的神经发育障碍,主要表现为社会交往困难、沟通障碍及重复行为等特征。研究显示,ASD 儿童的发育轨迹是动态的,受多种因素影响。对 ASD 机制的深入了解使神经可塑性(NP)和环境敏感期(ES)在干预效果中的重要性逐渐显现,尤其是干预时间窗的选择可能显著影响成效。因此,精准干预(PI)成为优化 ASD 儿童治疗的关键。本文探讨 ASD 儿童的发育轨迹,神经可塑性与环境敏感期的关系,以及如何制定更有效的干预策略,为 ASD 儿童的支持与治疗提供科学依据。

关键词: 孤独症谱系障碍; 动态发育轨迹; 神经可塑性; 环境敏感期; 精准干预

中图分类号:R749.94 文献标识码:A 文章编号:1008-6579(2026)03-0329-05 doi:10.11852/zgetbjzz2025-0163

Dynamic developmental trajectories and precision intervention based on neuroplasticity and environmental sensitivity periods in children with autism spectrum disorder

WEN Jing

Guiyang Maternal and Child Health Care Hospital, Guiyang, Guizhou 550003, China

Abstract: Autism spectrum disorder (ASD) is a complex neurodevelopmental condition characterized by impairments in social communication, interaction, and restricted, repetitive behaviors. Research indicates that the developmental trajectories of ASD children are dynamic and influenced by multiple factors. A deeper understanding of ASD mechanisms has highlighted the critical role of neuroplasticity (NP) and environmental sensitivity periods (ES) in intervention efficacy, particularly as the timing of interventions may significantly impact outcomes. Consequently, precision intervention (PI) has emerged as a key strategy for optimizing treatment in ASD children. This article explores the developmental trajectories of ASD children, the relationship between neuroplasticity and environmental sensitivity periods, and how to formulate more effective intervention strategies, thereby providing a scientific foundation for supporting and treating children with ASD.

Keywords: autism spectrum disorder; dynamic developmental trajectory; neuroplasticity; environmental sensitivity period; precision intervention

1 概述

孤独症谱系障碍(autism spectrum disorder, ASD)是一种影响儿童社交、沟通和行为的神经发育障碍,受多种生物和环境因素影响^[1]。研究发现 ASD 的发育轨迹是动态的,随着时间和环境变化而有所不同。神经可塑性(neuroplasticity, NP)和环境敏感期(environmental sensitivity period, ES)的概念为理解 ASD 干预提供了新视角,可能在不同发展阶段影响 ASD 儿童的症状表现和干预效果^[2]。

NP 指的是大脑在经历学习和环境刺激时的适应能力,尤其在儿童早期发育阶段尤为显著^[3]。研究表明,早期干预可以改善 ASD 儿童的社交和语言能力^[4],但效果受个体差异影响^[5],如初始语言能

力、智力水平及父母参与程度等。

ES 强调儿童在特定时间内对外部刺激的敏感反应,干预可能深远影响其发育。研究表明,ASD 儿童在早期阶段的社交沟通能力与后续发展密切相关,强调了在此敏感期内进行干预的重要性^[6]。因此,探索 ASD 儿童的动态发育轨迹及干预时间窗,有助于制定精准的干预策略,优化其发育结果和生活质量。

2 神经可塑性与环境敏感期对 ASD 干预的影响

2.1 ASD 的发育轨迹概述

2.1.1 ASD 的早期表现及诊断标准 ASD 在儿童早期表现出社交互动的困难、沟通能力的缺乏以及重复性行为 and 狭隘的兴趣等特征^[7]。根据《美国精

神障碍诊断与统计手册》第五版(Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, DSM-5), ASD 的诊断标准包括社交沟通缺陷及行为、兴趣的限制和重复性^[8]。早期的表现可能包括缺乏眼神交流、对他人情感的反应不足、语言发展延迟等^[2]。研究表明,父母的早期关注和对发展异常的识别对及时诊断至关重要,但许多儿童在出现早期症状后,直到学龄前才被正式诊断,错过了最佳干预时机^[9]。

2.1.2 ASD 的发育阶段及其变化特点 ASD 儿童的发育轨迹具有明显的阶段性特征,各年龄段的发育特点影响其症状和需求。早期阶段(0~3岁)是语言和社交技能发展的关键期,但 ASD 儿童社交兴趣或互动能力少^[10]。学龄前期(3~6岁)是认知和行为发展的关键期,ASD 儿童可能表现出更多重复性行为 and 狭隘兴趣^[11-12]。学龄期(6~12岁),儿童的认知和社交技能能进一步发展,存在个体差异,部分儿童适应良好,而 ASD 儿童面临更大社交和沟通挑战^[12]。青春期(12~18岁)是向成人过渡的关键时期,ASD 青少年面临更多社交焦虑和情绪问题^[13-14]。此外,ASD 儿童的症状也受家庭环境、社会支持和教育背景影响^[15]。

2.1.3 影响 ASD 发育轨迹的因素 ASD 的发育轨迹受多种因素影响,包括生物学、环境和社会因素。生物学因素如遗传易感性和神经发育异常是 ASD 的重要风险因素^[2]。环境因素如孕期药物或化学物质的暴露也可能增加风险^[16]。此外,家庭支持、教育资源和社会经济地位等社会因素对 ASD 儿童的发育有重要影响^[17]。研究表明,早期干预和支持能显著改善 ASD 儿童的发育结果,因此了解这些因素对制定有效干预策略至关重要^[18]。

2.2 神经可塑性在 ASD 中的作用

2.2.1 神经可塑性的基本概念 神经可塑性是大脑在学习、记忆、伤害或环境变化时重新组织神经连接的能力,涉及突触强度变化、新突触形成和神经元结构功能改变^[3,19]。在 ASD 中,神经可塑性被认为影响儿童的认知和社交能力,研究显示 ASD 患者在此方面存在异常,可能导致信息处理和社交认知缺陷,影响行为表现和发展轨迹^[20]。

2.2.2 神经可塑性与 ASD 的关系 ASD 发病机制复杂,涉及遗传和环境因素的相互作用。研究发现,ASD 儿童在早期发展阶段,神经可塑性受到基因突变、环境毒素和生物学因素等多种因素的影响,可能导致大脑发育异常,影响社交和语言能力^[21]。此外,早期干预被认为能促进神经可塑性,改善

ASD 儿童的认知和社交能力,强调了干预的重要性。

2.2.3 干预对神经可塑性的影响 干预措施对促进 ASD 儿童的神经可塑性至关重要。早期行为疗法、语言治疗和社交技能训练能有效改善其社交和沟通能力。个体化干预显著提高语言和社交技能,增强神经可塑性^[3]。此外,药物治疗和非侵入性脑刺激技术(如经颅磁刺激)也显示出改善 ASD 患者神经可塑性的潜力^[22]。因此,干预应关注提升神经可塑性的策略,以实现最佳治疗效果。

2.3 环境敏感期及其在 ASD 干预中的重要性

2.3.1 环境敏感期的定义与特征 环境敏感期是个体发育中对特定环境刺激反应敏感的阶段,尤其影响神经系统和行为发展^[23]。对于 ASD 儿童,在此期间适当的干预能显著改善发展结果,早期语言和社交技能干预效果最佳^[2]。此外,敏感期还增强了个体对环境变化的适应和学习能力,为干预提供了重要时机。

2.3.2 不同年龄阶段的环境敏感期分析 不同年龄阶段的儿童在环境敏感期表现不同。研究显示,早期儿童对语言刺激反应最敏感,早期干预能显著提高语言能力^[4]。随着年龄增长,神经可塑性降低,干预效果可能减弱。因此,针对 ASD 儿童的干预应尽早进行,以获得最佳效果。此外,儿童在不同发展阶段对社交行为和情感表达的敏感性也不同,这提示制定干预策略时应考虑年龄和发展阶段。

2.3.3 环境因素对 ASD 儿童的影响 环境因素对 ASD 儿童的发展至关重要。研究表明,母亲在怀孕期间的健康、生活方式和环境污染等因素可能影响儿童的神经发育,增加 ASD 风险^[24]。孕期接触某些化学物质或感染可导致胎儿神经发育异常,影响未来的社交和沟通能力^[25]。此外,家庭环境的支持对 ASD 儿童的参与度和社交能力有显著影响,支持性环境能促进他们在家庭和社区的参与^[26]。因此,识别和改善 ASD 儿童所处的环境因素,对于提高他们的生活质量和发展潜力至关重要。

2.4 干预时间窗的选择与优化

2.4.1 早期干预的必要性 早期干预被认为是改善儿童 ASD 发展轨迹的关键因素。研究显示,0~5岁期间的早期语言干预对 ASD 儿童的语言能力影响显著,尤其是 0~3 岁大脑神经可塑性最强,2~5 岁语言能力快速发展^[27]。此外,早期识别和干预能显著降低 ASD 儿童在社交、沟通和认知方面的长期障碍风险。早期介入不仅改善儿童的语言和社交技能,还能提高认知能力和适应能力,从而提升家庭整

体生活质量^[4]。因此,早期干预对个体发展及家庭和社会均有积极作用。

2.4.2 不同干预方法的时间窗比较 不同干预方法的实施时间窗差异显著,最佳干预时机应根据儿童的发育阶段和个体特征选择。行为疗法建议在儿童 2 岁前开始,以实现最大化干预效果,早期干预能显著改善 ASD 儿童的社交技能和语言能力^[5]。语言疗法则在 2~5 岁进行,此阶段儿童对语言刺激敏感,干预效果更显著^[28]。社交技能训练的最佳时间因儿童社交发展水平而异,但普遍认为学龄前期效果较好^[29]。父母参与的干预在早期尤为重要,能显著提升效果,并根据儿童表现灵活调整策略^[30]。专业治疗通常在儿童进入特定发展阶段后进行,以确保内容与发育水平匹配^[31]。选择干预方法时需综合考虑儿童的年龄、发育水平、症状严重程度及家庭环境,以确定最佳干预时间窗,并动态调整策略以确保有效。

2.4.3 干预效果的评估与反馈机制 干预效果的评估与反馈机制是确保干预成功的重要环节。有效的评估工具能实时监测儿童的发展变化,并根据反馈调整干预策略。采用标准化的评估工具如孤独症诊断观察量表(Autism Diagnostic Observation Schedule, ADOS)可对比干预前后的社交、沟通和行为变化^[32]。此外,定期反馈机制鼓励家长与专业人员沟通,有助于优化干预效果。研究表明,反馈机制增强家长参与感,提高儿童的积极性和配合度,从而提升整体效果^[33]。因此,完善的评估与反馈机制是实现精准干预(precision intervention, PI)的重要保障。

2.5 精准干预策略的探索

2.5.1 个体化干预方案的设计 个体化干预方案在儿童 ASD 治疗中至关重要,研究显示儿童的 ASD 特征、智商、语言能力及父母参与对语言能力有显著影响^[2]。因此,干预应基于每个儿童的具体情况,包括发展轨迹和家庭环境。方案制定需综合考虑症状严重程度、认知功能及社交能力,以提供有效支持。如早期语言干预(early language intervention)在儿童语言发展的关键期,通过系统策略支持有语言发展风险的儿童,促进其语言能力提升^[34]。研究表明,早期语言干预对所有 ASD 儿童都至关重要,强调了考虑个体差异的重要性^[5]。

2.5.2 多学科协作在干预中的应用 多学科协作(multidisciplinary collaboration)是在 ASD 儿童干预中整合不同学科的专业知识,以提供个体化支持^[35]。参与者包括语言病理学家、心理学家、行为

分析师等,他们共同制定和实施干预计划^[11]。这种模式能帮助儿童在语言、社交、行为和生活技能上取得更好发展。如早期介入丹佛模式(Early Start Denver Model, ESDM)显著改善了 ASD 儿童的认知和社交能力,效果优于常规干预^[36]。因此通过多学科协作,能够更好识别儿童需求,制定个性化计划,提高干预的有效性和可持续性,并动态调整策略以适应儿童的发展变化。

2.5.3 未来研究方向与临床实践的结合 未来研究应聚焦于将理论与临床实践结合,以提升 ASD 儿童干预效果。早期识别和干预能显著改善儿童社交和语言能力。因此,未来应探索更有效的筛查工具和干预策略,以便及时进行干预。同时,研究应关注家庭和社区参与,以增强干预效果。通过建立反馈机制和评估体系,可以优化干预方案,使其更符合儿童需求,实现精准干预^[37]。

3 ASD 干预策略的优化与未来研究方向

近年来,ASD 研究在理解儿童的发育轨迹、神经可塑性和环境敏感期方面取得了显著进展。大规模纵向研究显示,ASD 儿童在社交、语言和认知方面的变化趋势长期存在,因此在关键时间点实施精准干预尤为重要。在早期阶段的高峰期,优化干预措施能显著提升 ASD 儿童的发展。^[38]

然而,ASD 表现因个体差异而异,核心症状包括社交沟通障碍、重复行为和狭隘兴趣,表现形式和严重程度各异。部分儿童可能语言发育迟缓,而其他儿童在语言表达上正常但社交互动困难^[39]。此外,干预反应受遗传、神经发育、环境刺激和家庭支持等因素影响^[40]。个体化干预方案应根据儿童的具体症状、认知水平、语言能力、社交需求及家庭环境定制,以实现最大化干预效果。

未来研究应聚焦于整合个体差异,探索多样化干预方案。通过开发精细评估工具,识别 ASD 儿童在各方面的差异,研究者可以优化干预策略,动态调整和个性化设计方法,为 ASD 儿童创造更有利的发展环境,帮助他们在社交和沟通能力上取得更大进展,改善生活质量和社会适应能力。

参考文献

- [1] Botelho RM, Silva A, Borbely AU. The autism spectrum disorder and its possible origins in pregnancy[J]. Int J Environ Res Public Health, 2024, 21(3):244.
- [2] Song XK, So WC. The influence of child-based factors and parental inputs on expressive language abilities in children with autism spectrum disorder[J]. Autism, 2022, 26(6): 1477-1490.

- [3] Marzola P, Melzer T, Pavesi E, et al. Exploring the role of neuroplasticity in development, aging, and neurodegeneration[J]. *Brain Sci*, 2023, 13(12):1610.
- [4] Rollins PR, De Froy AM. Reexamining pathways early autism intervention in children before and after the third birthday: A randomized control trial[J]. *J Autism Dev Disord*, 2023, 53(3):1189-1201.
- [5] Morneau-Vaillancourt G, Andlauer T, Ouellet-Morin I, et al. Polygenic scores differentially predict developmental trajectories of subtypes of social withdrawal in childhood[J]. *J Child Psychol Psychiatry*, 2021, 62(11):1320-1329.
- [6] Journal F, Franchini M, Godel M, et al. Phenotyping variability in early socio-communicative skills in young children with autism and its influence on later development[J]. *Autism Res*, 2024, 17(10):2030-2044.
- [7] Rivera MD, Aponte SN, Rivera F, et al. MED13 gene mutation related to autism spectrum disorder: A case report[J]. *Cureus*, 2024, 16(5):e59904.
- [8] Klila H, Giuliani F. Autism spectrum disorder in verbal adults without intellectual disabilities (Asperger syndrome) [J]. *Rev Med Suisse*, 2021, 17(734):751-753. (in French)
- [9] Loo KK, Cheng J, Sarco D, et al. Diagnostic overshadowing: Insidious neuroregression mimicking presentation of autism spectrum disorder[J]. *J Dev Behav Pediatr*, 2022, 43(7):437-439.
- [10] Itskovich E, Zyga O, Libove RA, et al. Complex interplay between cognitive ability and social motivation in predicting social skill: A unique role for social motivation in children with autism[J]. *Autism Res*, 2021, 14(1):86-92.
- [11] Lin Q, Shi Y, Huang H, et al. Functional brain network alterations in the co-occurrence of autism spectrum disorder and attention deficit hyperactivity disorder[J]. *Eur Child Adolesc Psychiatry*, 2024, 33(2):369-380.
- [12] Chen Y, Luo J, Chen S, et al. Altered cortical gyrification, sulcal depth, and fractal dimension in the autism spectrum disorder comorbid attention-deficit/hyperactivity disorder than the autism spectrum disorder[J]. *Neuroreport*, 2023, 34(2):93-101.
- [13] Hughes MM, Shaw KA, Patrick ME, et al. Adolescents with autism spectrum disorder: Diagnostic patterns, co-occurring conditions, and transition planning[J]. *J Adolesc Health*, 2023, 73(2):271-278.
- [14] Hughes MM, Kirby AV, Davis J, et al. Individualized education programs and transition planning for adolescents with autism[J]. *Pediatrics*, 2023, 152(1):e2022060199.
- [15] Samadi SA, Mahmoodzadeh A, Foadgar M, et al. The childhood autism rating scale second edition (CARS2) and its applicability in an Iranian sample[J]. *Autism Res*, 2025, 18(3):541-552.
- [16] Fuselier MN, Guzik AG, Bakhshaie J, et al. Examining the relationship between anxiety severity and autism-related challenges during cognitive behavioral therapy for children with autism[J]. *J Autism Dev Disord*, 2024, 54(5):1849-1856.
- [17] Li H, Han M, Tang S, et al. Dynamic and static brain functional abnormalities in autism patients at different developmental stages[J]. *Neuroreport*, 2025, 36(4):202-210.
- [18] Schuchert SA, Khattar S, Tekkar P, et al. Exploring social stages of play through eye to I[®] intervention model[J]. *Clin Child Psychol Psychiatry*, 2024, 29(3):928-948.
- [19] Han Y, Yuan M, Guo YS, et al. The role of enriched environment in neural development and repair[J]. *Front Cell Neurosci*, 2022, 16:890666.
- [20] Chen Z, Wang X, Zhang S, et al. Neuroplasticity of children in autism spectrum disorder[J]. *Front Psychiatry*, 2024, 15:1362288.
- [21] Abirami GPP, Radhakrishnan RK, et al. The regulation of reactive neuroblastosis, neuroplasticity, and nutraceuticals for effective management of autism spectrum disorder[J]. *Adv Neurobiol*, 2020, 24:207-222.
- [22] Tian L, Ma S, Li Y, et al. Repetitive transcranial magnetic stimulation can improve the fixation of eyes rather than the fixation preference in children with autism spectrum disorder[J]. *Front Neurosci*, 2023, 17:1188648.
- [23] Herzberg MP, Nielsen AN, Luby J, et al. Measuring neuroplasticity in human development: The potential to inform the type and timing of mental health interventions[J]. *Neuropsychopharmacology*, 2024, 50(1):124-136.
- [24] Pham C, Symeonides C, O'Hely M, et al. Early life environmental factors associated with autism spectrum disorder symptoms in children at age 2-years: A birth cohort study [J]. *Autism*, 2022, 26(7):1864-1881.
- [25] Yuan JJ, Zhao YN, Lan XY, et al. Prenatal, perinatal and parental risk factors for autism spectrum disorder in China: A case-control study[J]. *BMC Psychiatry*, 2024, 24(1):219.
- [26] Simpson K, Adams D. Parent-reported environmental factors and strategies to support home and community participation in children on the autism spectrum[J]. *Disabil Rehabil*, 2024, 46(17):3970-3979.
- [27] Pecukonis M, Young GS, Brian J, et al. Early predictors of language skills at 3-years of age vary based on diagnostic outcome: A baby siblings research consortium study[J]. *Autism Res*, 2022, 15(7):1324-1335.
- [28] Pickles A, Wright N, Bedford R, et al. Predictors of language regression and its association with subsequent communication development in children with autism[J]. *J Child Psychol Psychiatry*, 2022, 63(11):1243-1251.
- [29] Tripathi I, Estabillio JA, Moody CT, et al. Long-term treatment outcomes of PEERS(®) for preschoolers: A parent-mediated social skills training program for children with autism spectrum disorder[J]. *J Autism Dev Disord*, 2022, 52(6):2610-2626.
- [30] Gibbard D, Roulstone S, Shadrack NIK, et al. A randomised controlled trial of the effectiveness of parent-based models of language intervention for 2- to 3-year-old children with speech, language and communication needs (SLCN) in areas of social disadvantage[J]. *Int J Lang Commun*

- Disord, 2024, 59(4):1517-1537.
- [31] Wood JJ, Kendall PC, Wood KS, et al. Cognitive behavioral treatments for anxiety in children with autism spectrum disorder: A randomized clinical trial[J]. JAMA Psychiatry, 2020, 77(5):474-483.
- [32] Simonoff E, Kent R, Stringer D, et al. Trajectories in symptoms of autism and cognitive ability in autism from childhood to adult life: Findings from a longitudinal epidemiological cohort[J]. J Am Acad Child Adolesc Psychiatry, 2020, 59(12):1342-1352.
- [33] Li L, Su YE, Hou W, et al. Expressive language profiles in a clinical screening sample of mandarin-speaking preschool children with autism spectrum disorder[J]. J Speech Lang Hear Res, 2023, 66(11):4497-4518.
- [34] Vermeij B, Wiefelerink CH, Knoors H, et al. Effects in language development of young children with language delay during early intervention[J]. J Commun Disord, 2023, 103:106326.
- [35] Wang L, Wang B, Wu C, et al. Autism spectrum disorder: Neurodevelopmental risk factors, biological mechanism, and precision therapy [J]. Int J Mol Sci, 2023, 24(3):1819.
- [36] Pruneti C, Coscioni G, Guidotti S. Evaluation of the effectiveness of behavioral interventions for autism spectrum disorders: A systematic review of randomized controlled trials and quasi-experimental studies[J]. Clin Child Psychol Psychiatry, 2024, 29(1):213-231.
- [37] Mira Coelho A, da Conceição V. Predictors in ASD: The importance of parents' perception[J]. Front Psychiatry, 2021, 12:506148.
- [38] Bondi BC, Tassone VK, Bucsea O, et al. A systematic review of neurodevelopmental assessments in infancy and early childhood: Developing a conceptual framework, repository of measures, and clinical recommendations[J]. Neuropsychol Rev, 2024.
- [39] Baumer NT, Pawlowski KG, Amaral JL, et al. Clinically derived 12-factor structure and confirmatory factor analysis of the neurodevelopmental parent report for outcome monitoring[J]. Front Psychiatry, 2023, 14:1243467.
- [40] Nohelty K, Bradford CB, Hirschfeld L, et al. Effectiveness of telehealth direct therapy for individuals with autism spectrum disorder [J]. Behav Anal Pract, 2022, 15(3):643-658.
- 收稿日期:2025-02-26 修回日期:2025-08-21 本文编辑:杨媛媛

收稿日期:2025-02-26 修回日期:2025-08-21 本文编辑:杨媛媛

(上接第 295 页)

- [9] Sorge RE, Lacroix-Fralich ML, Tuttle AH, et al. Spinal cord Toll-like receptor 4 mediates inflammatory and neuropathic hypersensitivity in male but not female mice[J]. *J Neurosci*, 2011, 31(43): 15450-15454.
 - [10] 林涛. TAK-242 通过抑制 TLR4-NF- κ B 通路减轻出血后脑积水的研究[D]. 济南: 山东大学, 2022.
Lin T. Pharmacological inhibition of TLR4-NF- κ B signaling by TAK-242 attenuates posthemorrhagic hydrocephalus [D]. Jinan: Shandong University, 2022. (in Chinese)
 - [11] Feng Y, Ju Y, Wu Q, et al. TAK-242, a toll-like receptor 4 antagonist, against brain injury by alleviates autophagy and inflammation in rats[J]. *Open Life Sci*, 2023, 18(1): 20220662.
 - [12] Hughes HK, Rowland ME, Onore CE, et al. Dysregulated gene expression associated with inflammatory and translation pathways in activated monocytes from children with autism spectrum disorder[J]. *Transl Psychiatry*, 2022, 12(1): 39.
 - [13] Rice TW, Wheeler AP, Bernard GR, et al. A randomized, double-blind, placebo-controlled trial of TAK-242 for the treatment of severe sepsis[J]. *Crit Care Med*, 2010, 38(8): 1685-1694.
 - [14] Sultan S, Alhejin N, Serafi R, et al. Does vitamin D deficiency increase the risk of autism spectrum disorder? Linking evidence with theory—A narrative review[J]. *Psychiatry Int*, 2025, 6(1): 22.
 - [15] Yu H, Lin L, Zhang Z, et al. Targeting NF- κ B pathway for the therapy of diseases: Mechanism and clinical study [J]. *Neurosci Biomed Res*, 2025, 10(1): 1-12.
 - [16] Mowry FE, Peaden SC, Stern JE, et al. TLR4 and AT1R mediate blood-brain barrier disruption, neuroinflammation, and autonomic dysfunction in spontaneously hypertensive rats[J]. *Pharmacol Res*, 2021, 174: 105877.
 - [17] 孙梦菲. 基于 TLR4/MyD88/NF- κ B 信号通路探讨汉黄芩素抑制小胶质细胞炎症并保护神经元细胞的实验研究 [D]. 北京: 中国中医科学院, 2024.
Sun MF. Experimental study on wogonin inhibiting microglial inflammation and protecting neuronal cells with wogonin based on TLR4/MyD88/NF- κ B signaling pathway [D]. Beijing: China Academy of Chinese Medical Sciences, 2024. (in Chinese)
 - [18] Wu X, He T, Yang C, et al. Suppressing TLR4 alleviates cerebral injury in heatstroke rats through the modulation of microglial polarization[J]. *Int J Hyperthermia*, 2025, 42(1): 2503312.
 - [19] Zhang X, Li J, Cao C, et al. Nrf2 activation by neferine mitigates microglial neuroinflammation after subarachnoid hemorrhage through inhibiting TAK1-NF- κ B signaling[J]. *Int Immunopharmacol*, 2024, 130: 111693.
 - [20] Hughes HK, Moreno RJ, Ashwood P. Innate immune dysfunction and neuroinflammation in autism spectrum disorder (ASD)[J]. *Focus*, 2024, 22(2): 229-241.
 - [21] Paolicelli RC, Sierra A, Stevens B, et al. Microglia states and nomenclature: A field at its crossroads[J]. *Neuron*, 2022, 110(21): 3458-3483.
- 收稿日期: 2025-09-02 修回日期: 2025-11-15 本文编辑: 杨媛媛

收稿日期:2025-09-02 修回日期:2025-11-15 本文编辑:杨媛媛