

· 特邀综述 ·

系统获得性抗性移动信号Pip/NHP研究进展

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摘要 系统获得性抗性(SAR)是一种因病原微生物初次侵染植物局部叶片而被激活的整株水平上的持久广谱抗性。在初次侵染部位快速产生的抗性信号, 可通过韧皮部传输到植物其它部位, 从而激活SAR。哌啶酸/N-羟基哌啶酸(Pip/NHP)作为新发现的移动信号分子, 在SAR信号通路中具有重要作用。该文综述了Pip/NHP的合成、转运以及对SAR调控作用的最新研究进展。

关键词 系统获得性抗性, 移动信号, 哌啶酸, N-羟基哌啶酸

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自局部侵染点激发的防御机制激活了植物远端部位乃至整株的系统防御反应, 以保护未感染组织免受病原体的后续入侵(Durrant and Dong, 2004), 这种长期、持久和广谱的诱导抗性被称为系统获得性抗性(systemic acquired resistance, SAR)。SAR激发需要水杨酸(salicylic acid, SA)的积累, 并导致标记基因病程相关基因1 (*Pathogenesis-Related Protein 1*, *PR1*)等一系列基因的转录重编程(van Loon et al., 2006; Park et al., 2007)。SAR在高等植物中普遍存在, 自20世纪60年代首次被发现, 因其生物学特性及其在植物保护中的潜在应用价值, 引起了科学家和农业科技人员的广泛关注(Tian and Zhang, 2019)。

SAR被激活时, 原发感染组织快速(数小时内)产生移动信号并传递到未感染系统组织, 进而触发其对亲和/不亲和病原体后续感染的免疫反应。SAR触发的关键步骤包括: (1) 在原发感染部位产生SAR信号; (2) SAR信号系统传递; (3) 系统组织信号感知; (4) 整株植物进入“防御准备就绪”状态。此外, SAR还具有跨代特性, 能将免疫“记忆”遗传给下一代(Luna et al., 2012; Slaughter et al., 2012)。同时, SAR存在产生、维持和消退过程。一次诱导产生的抗性一般可维持2–3周, 多次处理有时能获得更持久的抗性。然而, SAR的移动信号是什么? 如何协同实现

远程通信? 研究表明, 多个相关信号分子被认为是移动信号分子并得到广泛讨论(Dempsey and Klessig, 2012; Fu and Dong, 2013; Lucas et al., 2013; Shah and Zeier, 2013)。本文重点综述了近年新发现的植物信号分子哌啶酸(Pipecolic acid, Pip)/N-羟基哌啶酸(N-hydroxy-pipecolic acid, NHP)的生物合成途径、合成调控及Pip/NHP在SAR激活和失活中的重要调控作用。

1 潜在移动信号分子

最初, 由于在被病原体感染叶片韧皮部的分泌物中积累了大量SA, 因此SA被认为是远距离信号(Métraux et al., 1990; Yalpani et al., 1991)。为了确定SA是否真的是移动信号, 利用表达细菌SA降解酶(NahG)的转基因植物进行嫁接实验, 发现转基因烟草(*Nicotiana tabacum*)虽然不能积累SA, 但完全能够传递信号, 导致非转基因接穗对病原体感染产生抗性。研究表明, 植株需要在远离感染部位的组织中存在SA, 该信号才能诱导系统抗性。因此, SA不太可能是移动信号, 尽管其积累为诱导SAR所必需(Vernooij et al., 1994; Pallas et al., 1996)。其后发现多种化合物为SAR的潜在移动信号分子, 包括水杨

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酸甲酯(methyl salicylate, MeSA)、壬二酸(azelaic acid, AzA)、3-磷酸甘油醛(glyceraldehyde 3-phosphate, G3P)、脱氢枞酸(dehydroabietic acid, DA)、哌啶酸(Pip)和N-羟基哌啶酸(NHP)等(Jung et al., 2009; Chanda et al., 2011; Návarová et al., 2012; Bernsdorff et al., 2016)。

MeSA作为SA的挥发性衍生物, 首先被认为是能传递SA依赖型系统免疫的移动信号分子。MeSA作为一种移动信号分子, 通过韧皮部运输, 并在系统叶中被水解为生物活性分子SA, 进而触发SAR。同时, MeSA也可作为一种空气传播信号, 诱导相邻植物的抗病性(Park et al., 2007)。但在一些拟南芥(*Arabidopsis thaliana*)防御缺陷突变体中, MeSA的产生和SAR的诱导并不一致。例如, SA甲基转移酶(salicylic acid carboxyl methyltransferases, SAMT)基因表达缺陷的T-DNA插入突变体, 在被病原体入侵后完全没有诱导产生MeSA, 但在用丁香假单胞菌(*Pseudomonas syringae* pv. *maculicola*, Psm)接种局部叶后, SA水平上升并触发SAR。因此, 在拟南芥中, MeSA不是SAR所必需, 而SA在远端叶片中的积累通过异分支酸合成酶(Isochorismate Synthase 1, ICS1)从头合成途径实现(Attaran et al., 2009)。

虽然已证实AzA通过韧皮部运输(Jung et al., 2009; Lim et al., 2016), 但AzA在防御信号传输中的功能仍缺乏直接遗传证据。Zoeller等(2012)研究发现, AzA在感染携带*avrRPM1*基因的丁香假单胞菌番茄致病变种(*Pseudomonas syringae* pv. *tomato*, Pst) Pst DC3000的番茄(*Lycopersicon esculentum*)局部组织中大量积累, 在系统叶中却无积累, 但AzA仍可增强系统免疫强度。在拟南芥中, G3P脱氢酶(G3P dehydrogenase, G3PDH)突变降低了植株对Psm的SAR。其它G3P合成相关酶(如甘油激酶(glycerol kinase, GK))的突变也导致SAR的衰减, 而外施G3P可恢复其SAR表型, 表明G3P确实是系统免疫中的重要信号成分之一, 但外施G3P不足以诱导野生型植物的SAR(Chanda et al., 2011)。

针叶树可以分泌DA以应对受伤或虫害(Trapp and Croteau, 2001; Bohlmann and Keeling, 2008)。在拟南芥、烟草和番茄中, DA是SAR的有效激活剂, 可增强植物对病原体的抗性(Chaturvedi et al., 2012)。与Pto (*Pseudomonas syringae* pv. *tomato*

DC3000)分泌的AvrRpt2蛋白诱导SAR需较长时间相比, DA可在30分钟内诱导拟南芥的SAR。同位素标记实验表明, DA能在15分钟内从局部注射部位转移到系统组织, 并快速触发SAR。但Chaturvedi等(2012)提出, SAR的关键步骤是将DA从低生物活性LMW (low molecular weight fraction)池动员到高活性HMW (high molecular weight fraction)池中。用胰蛋白酶处理破坏AvrRpt2蛋白产生的叶柄分泌物(petiole exudates, PEX)诱导的SAR活性时, 也降低了HMW中的DA含量, 表明DA与HMW池中的蛋白质有关。然而, HMW池中的蛋白质是什么? 对于缺乏DA的植物, 还需更多的实验证据来确定DA是否为诱导SAR所必需(Chaturvedi et al., 2012)。最近的研究表明, DA通过诱导自主途径基因的表达下调开花抑制因子FLC (Flowering Locus C)进而调控开花, 自主途径基因在SAR中发挥作用, 但FLC无此效应。SA为DA诱导SAR所必需, 但并非DA诱导开花所必需(Chaturvedi et al., 2020)。

Pip/NHP为近5年来新发现的信号分子, 其在SAR信号中的作用被不断揭示, 成为公认的SAR移动信号。

2 SAR移动信号Pip/NHP

Pip由赖氨酸(lysine, Lys)通过AGD2样防御反应蛋白1 (Agd2-Like Defense Response Protein 1, ALD1)和SAR缺陷蛋白4 (SAR-Deficient 4, SARD4)催化合成(Gupta and Spenser, 1969; Song et al., 2004a; Zeier, 2013; Ding et al., 2016; Hartmann et al., 2017), 并通过黄素依赖性单加氧酶1 (Flavin-Dependent Monooxygenase 1, FMO1) (Chen et al., 2018; Hartmann et al., 2018)进一步转化为NHP。在SAR激活过程中, L-赖氨酸衍生的氨基酸衍生物N-羟基哌啶酸(NHP)和其生物合成前体哌啶酸(Pip)在接种病原菌的叶中合成, NHP和SA通过在系统叶中积累协调SAR的建立(Návarová et al., 2012; Bernsdorff et al., 2016; Chen et al., 2018; Hartmann and Zeier, 2018; Hartmann et al., 2018)。

2.1 Pip

2.1.1 Pip的发现及其生物合成

Pip是一种杂环非蛋白氨基酸, 是赖氨酸的分解代谢

产物,可作为吡哆醇依赖性癫痫的诊断标志物(Plecko et al., 2005),并在高哌啶酸血症患者体内累积,而高哌啶酸血症是一种罕见的隐性代谢紊乱症,与过氧化物酶体功能紊乱有关(Tranchant et al., 1993)。该衍生物还存在于地外陨石的非蛋白质氨基酸中(Kvenvolden et al., 1971)。在植物尤其是被子植物中, Pip含量在包括病原体感染的不同胁迫反应中升高(Pálfi and Dézsi, 1968)。尽管先前对ald1突变体的遗传学研究表明,氨基转移酶ALD1在局部和系统防御反应中起关键作用(Song et al., 2004a, 2004b),但直到近年才发现Pip的功能(Návarová et al., 2012)。研究表明: (1) ALD1在体外表现出对赖氨酸的底物偏好性,赖氨酸是植物和动物中Pip生物合成的假定前体(Song et al., 2004a; Vicente et al., 2012); (2) 拟南芥中Pip的生物合成依赖于ALD1 (Návarová et al., 2012); (3) ALD1作为赖氨酸分解代谢第1步反应的酶,直接催化L-赖氨酸的 α -氨基转移到一种氧乙酸上,优先形成丙酮酸,其次是 ϵ -氨基- α -酮己酸(ϵ -amino- α -ketocaproic acid, KAC)和丙氨酸(Ding et al., 2016; Hartmann et al., 2017)。通过KAC中间体的自发分子内环化和脱水,形成环脱氢丙烯酸(dehydropipecolic acid, DP)和酮亚胺1,2-DP,然后异构化为更稳定的烯胺互变异构体2,3-DP,从而形成Pip(Hartmann et al., 2017)。

2.1.2 Pip生物合成途径的调控

病原体诱导的Pip积累水平在sard4突变体植株局部接种组织中仅略微降低,但在远端叶中大幅降低,表明SARD4主要介导全身组织中Pip的合成与积累,从而有利于诱导SAR (Ding et al., 2016)。而ALD1和SARD4的表达受SARD1和钙调蛋白结合蛋白60 g (Calmodulin-Binding Protein 60-Like G, CBP60g) (Sun et al., 2015)的正向调节。Sun等(2020)报道TGA1 (TGACG Motif-Binding Factor 1)和TGA4为SARD1和CBP60g转录所必需,并且SARD1是TGA1的直接靶基因, TGA1和TGA4通过调节SARD1和CBP60g的表达参与调节Pip的生物合成。此外,有研究表明,在ics1、npr1和pad4突变体的所有叶片中Pip的积累水平均降低,因此SA、NPR1 (Non-Expressor of PR Genes 1)和PAD4 (Phytoalexin-Deficient 4)可促进系统组织中Pip的生物合成(Návarová et al.,

2012)。Pip还可激活SA和Pip生物合成中正调控基因的表达,包括CBP60g、SARD1、PAD4和EDS1 (Enhanced Disease Susceptibility 1) (Kim et al., 2020)。与此类似,在被病原体局部感染引发SAR后, ALD1可在全身叶片中被诱导,其调控合成的Pip能从接菌局部叶转移到未接菌系统叶(Návarová et al., 2012; Wang et al., 2018b),推测Pip可通过上调CBP60g、SARD1、PAD4和EDS1表达以刺激自身和SA的合成。此外,在Pst分泌的avrRpt2蛋白诱导的系统叶片中, Pip从头合成需要G3P和SA (Wang et al., 2018a)。最新研究表明,钙离子依赖蛋白激酶5 (Ca-Imodulin-Domain Protein Kinase 5, CPK5)可通过调节SARD1的表达来调节Pip的生物合成(Guerra et al., 2020)。

2.2 NHP

2.2.1 NHP的发现及其生物合成

自Hartmann等(2018)首次报道NHP是拟南芥中天然积累的一种防御性代谢产物以来,一系列研究为其在不同物种SAR中起关键作用提供了证据(Chen et al., 2018; Hartmann et al., 2018; Holmes et al., 2019; Schnake et al., 2020)。在接种病原菌后,拟南芥和其它植物的叶片经历了大量代谢变化,导致游离芳香族氨基酸、支链氨基酸和赖氨酸大量产生(Návarová et al., 2012; Vogel-Adghough et al., 2013)。L-Pip可在黄素腺嘌呤二核苷酸、还原型烟酰胺腺嘌呤二核苷酸磷酸和分子氧存在的条件下由FMO1催化生成NHP。通过供应根部生理剂量的Pip进行RNA-seq分析,发现拟南芥SAR由Pip触发、FMO1依赖的防御基因转录激活介导。对叶片提取物进行差异代谢物筛选,并辅以同位素标记的途径前体叶片共渗研究和GC-MS分析,在植物中检测到FMO1依赖、L-Lys衍生和Pip衍生的NHP积累。此外,利用重组表达的FMO1蛋白进行体外生化分析,证明FMO1直接介导L-Pip将N-羟基化为NHP (Hartmann et al., 2018)。之后不久,通过烟草瞬时表达实验,拟南芥FMO1作为NHP合成N-羟化酶的效应得到证实(Chen et al., 2018)。除游离NHP外,还在拟南芥中检测到一种NHP-己糖结合物(Chen et al., 2018; Hartmann and Zeier, 2018)。最近的一系列研究阐明了哌啶酸途径的生化特性,并为NHP在SAR激活中的核心作用提供了多项证据。

2.2.2 NHP生物合成途径的调控

外源Pip在拟南芥中能诱导*FMO1*依赖型转录反应, 且与SAR反应高度重叠, 表明NHP能触发一系列SAR调节基因的表达(Hartmann et al., 2018)。值得注意的是, 这些基因包括NHP生物合成基因*ALD1*、*SARD4*和*FMO1*, 与SA生物合成相关基因*ICS1*和*EDS5* (*Enhanced Disease Susceptibility 5*), 以及调节基因*EDS1/PAD4*和*SARD1/CBP60g*。与此一致, 将NHP直接施用于叶片, 可导致*ALD1*、*SARD4*、*FMO1*和*ICS1*表达上调(Chen et al., 2018)。这些发现表明NHP可加强自身的生物合成, 积极调节SA的生物合成, 并构成上述SAR转录重编程所需扩增环的中心驱动力。

3 Pip/NHP移动信号及其对SAR的调控作用

3.1 Pip/NHP信号的长距离传递

根据接种病原菌后诱导SAR的叶柄分泌物中Pip的选择性富集, Návarová等(2012)提出了SAR中Pip在筛管中移动的可能性。研究发现, 用¹⁴C-放射性标记Pip局部叶片进行渗透, 导致¹⁴C-Pip在没有病原体的情况下转移到远端的叶片, 并且这种局部施用的Pip能以剂量依赖方式系统性地提高植株抗性(Wang et al., 2018a)。值得注意的是, 在另外2项研究中, Pip渗入叶片后既未引起局部也未引起系统性抗性效应(Návarová et al., 2012; Chen et al., 2018)。此外, Pip在*sard4*突变体植株的局部接种叶片中积累到相对较高的水平, 而在系统叶片中的积累显著延迟和减弱, 这些证据支持以下假设: 在生理条件下, Pip不会大量从局部运输到系统叶片(Ding et al., 2016; Hartmann et al., 2017)。与施用Pip相比, 用NHP处理局部叶片提高了野生型和*fmo1*植株的系统免疫抗性, 并且在NHP缺陷*fmo1*植株的远端叶片中检测到NHP-己糖结合物。该结果表明NHP或其己糖衍生物具有移动性(Chen et al., 2018)。然而, 仍不能排除Pip和NHP的叶间转移存在人为干扰, 因为大量Pip和NHP向叶片质外体空间的渗透可能会创造一个高度人工的实验环境, 从而有利于其以非生理方式在组织与器官之间转移代谢物。

3.2 Pip/NHP信号对SAR的调控

3.2.1 NHP与SA互作对SAR的调控

在接种病原菌或外施SA后, 叶片SA水平升高, 直接诱导一系列防御相关基因的表达, 并增强植物对兼性和寄生营养病原菌侵染的抵抗力(Delaney et al., 1995; Nawrath and Métraux, 1999; Thibaud-Nissen et al., 2006)。当用Pip预处理时, 野生型拟南芥中SA诱导*PR1*表达量升高, 但*fmo1*突变体中*PR1*表达量没有升高(Bernsdorff et al., 2016)。而在SA生物合成缺陷突变体*sid2*中, 外施Pip和NHP诱导的抗性也显著低于野生型(Hartmann et al., 2018), 表明NHP具有放大SA诱导抗性反应的重要功能。而*ald1*和*fmo1*抗病性的实验结果表明, 在病原体诱导的SAR中, NHP促进未感染的系统组织, 而不是接种局部组织SA的生物合成(Mishina and Zeier, 2006; Návarová et al., 2012; Bernsdorff et al., 2016; Hartmann et al., 2018)。在接菌叶片中, SA的初始升高先于Pip和NHP的积累。因此, 在这一阶段NHP不能促进SA的生物合成。与此相反, 在远端叶片中, NHP水平在SA与开始积累之前升高(Hartmann et al., 2018)。因此, NHP和SA途径间对兼性营养性病原体侵染的抗性诱导存在积极的互作效应, 这种效应类似于茉莉酸和乙烯信号在植物防御坏死营养菌中的协同作用(Memelink, 2009)。然而, NHP途径也具有独立于SA的分支, 实验表明, 无论是外施SA还是SAR本身, 都可在SA缺乏的突变体中观察到NHP和Pip诱导的抗性效应(Bernsdorff et al., 2016; Hartmann et al., 2018)。NHP和SA信号部分独立存在于基础免疫中, 导致SA和Pip/NHP缺陷的*sid2/ald1*双突变体对细菌侵染的基础抵抗力比各自单突变体更弱(Bernsdorff et al., 2016)。

3.2.2 NHP通过NPR1激活SAR

SA触发的防御反应由转录共激活子NPR1介导。在接种病原体时, SA水平提升促使NPR1从细胞质转移到细胞核(Mou et al., 2003)。随后SA与NPR1结合, 促进致病相关基因的表达, 从而激活免疫反应(Wu et al., 2012; Ding et al., 2018)。同时, NPR1也是病原体诱导SAR的必要成分(Ding et al., 2020)。在拟南芥*npr1*敲除突变株中, 外部喷施Pip引发的SAR反应大幅减弱, 表明NHP途径也通过NPR1传递信号

(Návarová et al., 2012)。拟南芥*npr1*突变体被细菌和卵菌病原体感染时, 外源NHP始终无法诱导SAR (Liu et al., 2020; Yildiz et al., 2021)。当NHP施于*sid2*的局部叶片时, 远端叶片产生中度的SAR反应, 但*npr1*单突变体和*sid2/npr1*双突变体无SAR反应。这表明NHP通过1个主要依赖SA和NPR1的途径诱导SAR, 以及1个次要并独立于SA但仍然依赖NPR1的途径诱导SAR。与此一致, *npr1*中NHP诱导的转录反应损失比*sid2*植物中的更严重(Yildiz et al., 2021)。

目前, 尚不清楚NPR1如何连接NHP和SA的免疫激活功能。一方面, NHP可能提高NPR1作为SA受体的活性水平, 从而增强SA触发的植物免疫。事实上, NPR1的转录水平随着外源NHP或Pip反应增强而升高(Hartmann et al., 2018; Yildiz et al., 2021), 且在*camta1/2/3/sid2*背景下, NHP的水平与叶提取物中NPR1蛋白总量呈正相关(Kim et al., 2020; Sun et al., 2020)。然而, 此时NPR1并未在细胞核中积累, 而核积累是其在防御基因转录中发挥功能的必要条件之一(Kim et al., 2020)。此外, 发现在植物维持基本转录水平时, NPR1足以全面激活SAR (Ding et al., 2020)。考虑到SA和NHP在羧酸和羟基类似结构方面的相似性, NPR1也可同时作为SA和NHP的受体来转导NHP免疫应答。然而, 竞争结合实验未能检测到NHP与NPR1的结合, 此时SA已被NPR1结合。有趣的是, NPR1与其同源蛋白NPR3/4也在NHP生物合成和SA稳态中发挥重要作用(Liu et al., 2020)。

3.2.3 NHP糖苷(酯)化对SAR的负调控

伴随NHP的发现, NHP-葡萄糖结合物也被发现在接种病原菌的拟南芥叶片中积累, 并依赖于NHP生物合成基因*ALD1*和*FMO1* (Chen et al., 2018; Hartmann and Zeier, 2018; Hartmann et al., 2018)。在寻找NHP糖基化酶的过程中, UGT76B1很快成为主要的候选酶, 因为UGT76B1转录水平与NHP生物合成基因在受病原体入侵时都系统性上调, 且外施Pip时也是如此(Bernsdorff et al., 2016; Hartmann et al., 2018; Hartmann and Zeier, 2019)。事实上, 最近的4项独立研究表明, 拟南芥叶片中存在天然的NHP-N-O-葡萄糖苷(NHP-N-O-glucoside, NHPG), 且受病原体诱导、SA促进并依赖于NHP和UGT76B1 (Bauer et al., 2021; Cai et al., 2021; Holmes et al., 2021;

Mohnike et al., 2021)。纯化的重组UGT76B1在体外以UDP葡萄糖作为活化葡萄糖形式, 将NHP转化为NHPG (Bauer et al., 2021; Cai et al., 2021; Holmes et al., 2021; Mohnike et al., 2021)。此外, 第2种NHP结合物NHP葡萄糖酯(NHP glucose ester, NHPGE)也在拟南芥中积累, 以响应病原体的入侵, 但独立于UGT76B1和SA信号途径(Hartmann and Zeier, 2018; Bauer et al., 2021)。

在拟南芥叶片中, UGT76B1具有强烈的病原体诱导性并系统性上调。接种病原菌的*ugt76b1*突变体代谢表型表明, UGT76B1介导NHPG的生物合成, 并主要参与响应病原体攻击的SAG积累通路。值得注意的是, 在拟南芥中过表达UGT76B1使NHP和SA向着各自β-葡萄糖苷的形成方向移动, 从而大幅降低游离NHP和SA在接种病原菌植株局部叶中的积累, 并完全消除了其在远端叶组织中的积累。因此, UGT76B1过表达植株基础免疫力降低并完全丧失SAR (Bauer et al., 2021; Cai et al., 2021)。与此类似, 当拟南芥UGT76B1与*ALD1*和*FMO1*在番茄小叶中瞬时共表达时, 局部组织中的NHPG合成增加, 而NHPAC累积减少, 这消除了仅共表达*ALD1*和*FMO1*时触发远端小叶中SAR反应的可能性(Mohnike et al., 2021)。上述研究表明, UGT76B1在病原体诱导积累后同时降低了活性NHP和SA的水平, 因此其在SAR信号转导终止中具有重要作用。

4 总结与展望

植物在被病原菌感染后, SAR移动信号激发系统抗性, 其活性与SA的积累有关, 并可通过不依赖于SA的信号通路产生反应。如图1所示, 在强致病菌与植物相互作用过程中, Pip/NHP通过SA非依赖和SA依赖途径诱导SAR。当植株受到病原菌感染时, 积累的NHP可以从受到入侵的局部叶片移动到远端的系统叶片, 并诱导转录反应, 该反应通过SA积累得到加强, 并在很大程度上依赖于NPR1。同时, NHP也可能通过不依赖SA的途径诱导SAR。如果侵染情况加重, NHP的积累也会导致植物体内SAR反应增强, 而且SA会增强NHP通过依赖于NPR1途径诱导的防御反应。一方面, Pip/NHP可诱导局部和全身组织中SA的合成; 另一方面, 系统组织中Pip/NHP的从头合成

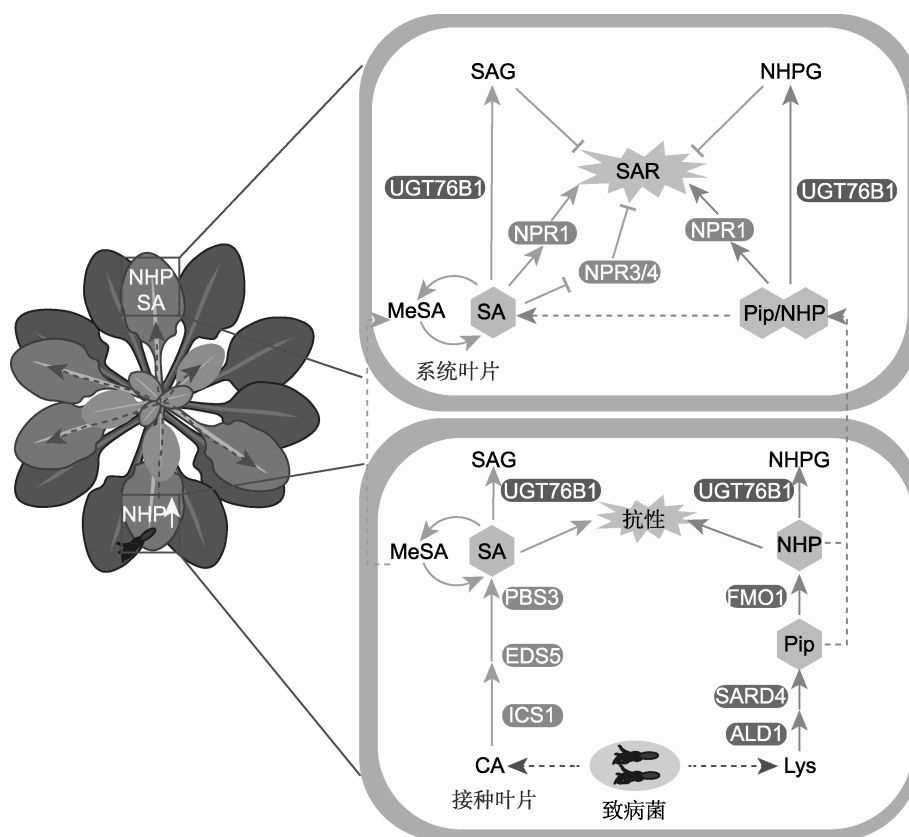


图1 哌啶酸(Pip)/N-羟基哌啶酸(NHP)的生物合成途径及其对系统获得性抗性(SAR)的调控作用

图示病原体诱导的SAR建立过程中的调控网络。NHP与水杨酸(SA)共同驱动主要的SAR诱导途径。SA由ICS1、EDS5和PBS3从分支酸(CA)开始合成, Pip由ALD1和SARD4从赖氨酸(Lys)开始合成, 再通过FMO1进一步合成NHP。Pip/NHP可通过韧皮部转运到远端叶片, 而SA通过SA甲基转移酶(MeSA)的形式转移到远端叶片。因此, 系统叶组织中的NHP水平开始升高, 从而启动NPR1依赖的转录SAR反应, 且NHP水平升高优先于SA, 因此NHP还能通过间接上调SA的方式激活SAR反应。此外, NHP/SA诱导的转录反应通过增加UGT76B1和其它分解代谢酶的活性, 将SA和NHP转化成葡萄糖基水杨酸(SAG)和NHP-N-O-葡萄糖苷(NHPG), 从而降低SAR活性代谢物NHP和SA的水平, 在系统水平上降低或终止SAR反应。棕色路线代表SA途径; 蓝色路线代表Pip/NHP途径; T型箭头表示抑制作用; 棕色和蓝色虚线表示长距离运输; 红色虚线表示病原菌的诱导。

Figure 1 Biosynthetic pathway of pipelicolic acid (Pip)/N-hydroxy-pipelicolic acid (NHP) and its regulation in systemic acquired resistance (SAR)

Figure shows a schematic diagram of regulatory network in the process of pathogen induced SAR establishment. NHP and SA jointly drives the main SAR induction pathway. While SA is synthesized from chorismic acid (CA) by ICS1, EDS5 and PBS3, Pip is synthesized from Lys by ALD1 and SARD4, and then NHP is further synthesized by FMO1. Pip/NHP can be transported to distal leaves through phloem, while SA can be transferred to distal leaves in the form of MeSA. Therefore, the level of NHP in leaf tissue of the system begins to rise, which starts the NPR1 dependent transcriptional SAR response, and the increase of NHP level takes priority with SA, which means, NHP can also activate the SAR response by indirectly upregulating SA. In addition, NHP/SA induced transcriptional response converts SA and NHP into SA-O-b-glucoside (SAG) and NHP-N-O-glucoside (NHPG) by increasing the activities of UGT76B1 and other catabolic enzymes, thereby reducing the levels of SAR active metabolites NHP and SA and reducing or terminating SAR response at the system level. Brown route represents SA pathway; Blue route represents Pip/NHP pathway; T-shaped arrow indicates inhibition; Brown and blue dotted lines indicate long-distance transportation; Red dotted line indicates the induction of pathogen.

也需要SA, 并依赖于SA信号通路的参与者(如NPR1)。尽管关于SAR信号通路研究已取得了许多重要进展, 但其详细机制仍有待进一步阐明。

有研究表明, 施用ROS、AzA或G3P可在ald1植株中诱导SAR, 但外部喷洒SA不能诱导ald1植株的SAR。此外, 外施Pip不能在no (noa1和nia2)、ros

(*rbohD/rbohF*)、*aza* (*mgd1/dgd1*)和*g3p* (*gly1/gli1*)等突变体中诱导SAR。以上表明Pip在ROS上游发挥作用。与拟南芥不同,经Pip处理或过表达*ALD1*的本氏烟草(*N. benthamiana*)中,*FMO1*的瞬时过表达导致高水平游离NHP的积累(Chen et al., 2018; Holmes et al., 2019)。这表明拟南芥和本氏烟草对游离NHP的耐受性不同,或者本氏烟草缺乏合成N-O-Glc-Pip的酶。局部施用Pip并未提高局部或远端组织中的N-Glc-Pip水平(Chen et al., 2018),说明Pip向N-Glc-Pip的转化可能仅在病原体感染时发生。这也暗示Pip可能通过多种途径诱导SAR,*FMO1*介导的NHP生物合成是其中的一个分支。然而,NHP-己糖结合物的确切化学性质以及产生的生物化学和生物功能是什么?是否有其它NHP衍生代谢物?确保Pip/NHP从接种局部叶远距离传输到系统叶的基本生理原理是什么?NHP信号转导的下游是什么?是否存在特定的NHP受体?SA与NHP之间协同相互关系的分子基础是什么?NHP与其它信号通路之间是否存在额外的相互作用?不同病原体(如细菌、真菌和病毒)在诱导SAR反应时Pip/NHP是否会产生不同的反应?上述一系列问题尚需深入研究。

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Research Progress of Mobile Signal Pip/NHP in Systemic Acquired Resistance

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Abstract Systemic acquired resistance (SAR) is a long-lasting broad-spectrum resistance at the whole plant level activated by the primary infection of pathogenic microorganisms at local leaves. The signals generated rapidly at the initial infection site can be transmitted to other parts of the plant through the phloem to activate SAR. Pipecolic acid (Pip) and N-hydroxy-pipecolic acid (NHP), as newly discovered mobile signal molecules, play important roles in SAR signaling pathway. Here, we mainly review the latest research progress in the synthesis, transportation of Pip/NHP and their regulation of SAR.

Key words systemic acquired resistance, mobile signal, Pipecolic acid, N-hydroxy-pipecolic acid

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