



中链脂肪酸抗菌和诱导防御肽表达的功能及其在仔猪饲料中的应用

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摘要: 近年,越来越多的研究表明,中链脂肪酸(MCFAs)抵抗病原菌是哺乳动物先天防御系统的重要组成部分,而且MCFAs也能够诱导人、猪和鸡内源性防御肽的表达,MCFAs的这些新功能尚未引起重视。MCFAs还和饲用有机酸或饲用植物精油具有协同抗菌增效作用,可以减少这些活性物质的使用量。相比于长链脂肪酸,日粮中添加MCFAs能显著地提高动物机体内氧气消耗量和线粒体呼吸速率,但产生活性氧自由基少,特别适合幼龄动物肠代谢和肝代谢所需的快速能量供应特点。日粮添加低浓度MCFAs(0.1%—0.5%,质量比)能显著提高新生或断奶仔猪存活率、粗蛋白粗脂肪消化率、饲料转化率,调节肠道菌群和改善肠上皮结构,进而促进生长。基于MCFAs的上述功能,将MCFAs与饲用有机酸或植物精油复配制备成微囊颗粒,可能是其用于仔猪抗生素替代品的尚佳方式。

关键词: 中链脂肪酸; 先天防御系统; 协同抗菌; 防御肽; 仔猪

Functions of Antibacterial and Inducing Defense Peptide Expression of Medium-Chain Fatty Acid and Its Application in Piglet Feeds

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Abstract: In recent years, more and more studies have shown that medium-chain fatty acid (MCFAs) resistance to pathogenic bacteria is an important component of innate defense system of mammals, and MCFAs can also induce expressions of endogenous host defense peptides (HDPs) in human, pig and chicken. However, these new functions of MCFAs have not attracted much attention. MCFAs also have a synergistic antibacterial synergistic effect with feeding organic acids or feeding plant essential oils, which can reduce the use of these active substances. In addition, compared with long-chain fatty acids, the addition of MCFAs in the diet can significantly increase the oxygen consumption and mitochondrial respiration rate in the body of animals, but it produces less reactive oxygen species, which is in line with the characteristics of rapid energy supply required by intestinal metabolism and liver metabolism in young animals. Adding low concentration of MCFAs (0.1%-0.5%, mass ratio) to the diet can significantly increase the survival rate of newborn or weaned piglets, the digestibility of crude protein and crude fat as well as the feed conversion rate, regulate the intestinal flora, and improve the intestinal epithelial structure, thus promoting the growth of animals. Based on the above advantages of MCFAs, mixing MCFAs with forage organic acid or plant essential oil to prepare coated particles may be a good way to use it as a substitute for antibiotics in piglets.

Key words: medium chain fatty acid; innate defense system; host defense peptide; synergistic antibiotics; piglets

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0 引言

瑞典雀巢公司基于大量医学和兽医学文献分析后对抗生素促生长机理进行了概述,称“抗生素对人和动物的促生长效应主要是减少了病原菌感染及其伴随的炎症响应造成的热量负担(因为在良好卫生状况下不能观察到抗生素的促生长效应)”^[1]。中链脂肪酸(medium-chain fatty acids, MCFAs)不仅具有良好的抑菌或杀菌、抗病毒和抗寄生虫作用^[2-4],而且能够改善肠道健康^[5-7]和提高饲料消化率^[8-9]。近年新的研究发现,MCFAs 抵抗病原菌是幼龄动物先天防御系统的重要组成部分,而且 MCFAs 能够诱导人和动物体内宿主防御肽(host defensin peptides, HDPs)的表达^[10-12],被认为是一种良好的免疫增强剂。早前报道的综述主要针对 MCFAs 的杀菌或抑菌活性^[8,13-14],以及 MCFAs 对仔猪生产性能的影响^[3,8,15-19],均未涉及 MCFAs 诱导宿主防御素表达的内容。本文主要综述了 MCFAs 在哺乳动物先天防御中的重要作用、诱导宿主防御肽表达、协同抗菌增效、代谢优势机理几个方面的新进展及其在仔猪抗生素替代品中的应用前景。本文还介绍了微囊化技术在避免中链脂肪酸难闻气味、减少添加量和延长肠道作用时间中的优势。

1 中链脂肪酸具有良好体外抑菌或杀菌作用,化学性质稳定

脂肪酸是重要的有机化工和精细化工原料,目前从天然动植物油脂经水解、精馏生产的脂肪酸占脂肪酸总量的 4/5 以上,是世界脂肪酸的主要来源^[20]。脂肪酸根据碳链的长度分为短链、中链和长链脂肪酸 3 种,通常把含有 6—12 个碳原子的直链饱和脂肪酸称为中链脂肪酸。MCFAs 资源来源广,自然界中天然存在的 MCFAs 都是偶数碳长,包括己酸(C6)、辛酸(C8)、癸酸(C10)和月桂酸(C12),主要存在于椰子油(含 60%)^[21-23]、棕榈油(含 8%)、萼距花属植物油中^[24]。MCFAs 具有良好的抑菌或杀菌作用,很早就被用于饲料(尤其用于青贮饲料)和食品防腐中^[4]。体外试验已经证明 MCFA 及其单甘油酯都能够抑制或杀死致病菌、病毒和寄生虫^[3,25]。总的来讲,中链脂肪酸(己酸、辛酸、癸酸和月桂酸)及其脂肪酸甘油一酯(辛酸甘油酯、癸酸甘油酯和月桂酸甘油酯)和长链不饱和脂肪酸(棕榈烯酸、

棕榈油酸、油酸、顺式-8-十八碳烯酸和亚油酸)抑菌活性较强,脂肪醇(正辛醇、正葵醇和月桂醇)次之,长链饱和脂肪酸(肉豆蔻酸、软脂酸和硬脂酸)抑菌效果相对较弱^[26-27]。MCFAs 主要作用于细菌的细胞膜,其两亲性的化学结构可以破坏细菌细胞膜的结构,导致细胞内容物流出和细胞裂解,从而导致细菌死亡^[28-30],这种机制也使得致病菌很难对其产生耐药性^[31-32]。

值得注意的是,中链脂肪酸(辛酸、癸酸、月桂酸)与有机弱酸(乙酸、乳酸、苹果酸、柠檬酸)对 *E.coli* O157:H7 具有极强的协同杀菌作用,癸酸与柠檬酸的协同杀菌能力最强;例如,无杀菌效应的 0.125mmol·L⁻¹ 的癸酸(约 0.002%)与无杀菌效应的 0.125mmol·L⁻¹ 的乳酸、0.125mmol·L⁻¹ 苹果酸、0.125 mmol·L⁻¹ 柠檬酸(约 0.0015%)分别组合后能显示极强的协同杀菌效应,其杀菌活力的 Log CFU 值在协同前后的变化分别为 2、3、6,如果提高组合的浓度,协同杀菌能力更强^[33]。中链脂肪酸(辛酸,癸酸和月桂酸)与食用植物精油(香芹酚,丁香酚,β-间苯二酸,反式肉桂醛,百里酚和香兰素)复合,对 *E.coli* O157:H7 的杀菌作用同样大大增强^[34]。采用辛酸和牛至精油的组合处理沙门氏菌、单核细胞增生性李斯特菌、大肠杆菌和金黄色链球菌时,发现辛酸和牛至精油表现出良好的协同效应^[35]。比例为 2:1:1:5:2:2 的辛酸、香芹酚、癸酸、肉桂醛、丁香酚、己酸复合配方对大肠杆菌、沙门氏菌和金黄色葡萄球菌的抑菌性能高且在模拟胃肠液环境中同样具有良好的抑菌作用^[36]。断奶是养猪生产中最具挑战性和关键性的阶段之一^[37]。仔猪断奶后通常有一个生长延滞期,主要是因为胃内盐酸和胰酶分泌不足导致消化能力低,以及日粮和环境因素改变等应激导致的采食量下降和腹泻^[38]。日粮中加入弱的有机酸降低胃肠道 pH 值能一定程度缓解这个问题,常用的有机弱酸主要是柠檬酸、甲酸、丙酸、乳酸、富马酸、苯甲酸等^[39]。体外模拟盲肠系统证实辛酸钠可以显著减少大肠杆菌和沙门氏菌的数量^[40],通过断奶仔猪口服鼠伤寒沙门氏菌或产肠毒素大肠杆菌构建的两个实验模型,证实了从椰子油中提取的中链脂肪酸盐混合物能够减小沙门氏菌或大肠杆菌等条件致病菌在肠道定植的活性^[41]。因此 MCFAs 在预防和治疗仔猪腹泻方面将有较大的应用前景,且与有机酸或植物精油复合使用杀菌效果可能更好。

2 中链脂肪酸抵抗病原菌是哺乳动物先天防御系统的重要组成部分

脂质的抗菌作用在 20 世纪 60 年代前后被发现, 但近年来人们才开始认识到脂肪酸是许多生物抵抗病原菌的先天防御系统的重要组成部分, 尤其是在皮肤和黏膜表面的防御中, 包括哺乳动物、两栖动物、软体动物、植物、藻类^[26, 28, 42-43]。哺乳动物母乳^[24, 42]、皮肤^[26, 44-45]、粘膜^[42]中都存在高含量的中链饱和脂肪酸和长链不饱和脂肪酸, 它们是这些组织抵御病原微生物最活跃的抗菌剂, 其作用比以前想象的更为重要^[26, 42, 44-47]。例如人的皮肤中每平方厘米含有 10—15 μg 的游离脂肪酸, 其中月桂酸 (C12)、肉豆蔻酸 (C14)、棕榈酸 (C16)、sapienic acid (C16:1n-10)、cis-8-octadecenoic acid (C18:1n-10) 含量最丰富^[28]。测试细菌对丙酮提取的前臂皮肤的敏感性试验发现, 化脓性链球菌和金黄色葡萄球菌在脂质减少的情况下的存活时间明显长于未经处理的皮肤^[48]。动物母乳中含有大量抗菌的 MCFAs (己酸 C6、辛酸 C8、癸酸 C10、月桂酸 C12) 和 LCFAs (主要是油酸 C18:1、亚油酸 C18:2、亚麻酸 C18:3), 其中中链脂肪酸占乳脂的比例高, 兔 (58%)、大鼠 (58%)、马 (48.1%)、山羊 (34.7%)、奶牛 (20.7%)、人 (11.7%)、猪 (4.1%)^[24, 49]。以低脂牛奶为唯一牛奶来源的儿童发生急性胃肠道疾病的可能性比服用全脂牛奶的儿童高 5 倍^[50]。高脂肪牛奶饮食喂养可以减少李斯特菌在大鼠肠黏膜的定植^[51]。由此可见, MCFAs 在皮肤和黏膜屏障功能中发挥重要作用, 是哺乳动物先天防御系统的重要组成部分。

3 中链脂肪酸能够诱导人、猪和鸡内源防御肽的表达

宿主防御肽 (Host defensin peptides, HDPs) 是小于 50 个氨基酸的短肽, 一般带正电荷, 具有两亲性, 广泛存在于植物界和动物界^[52-53]。HDPs 是先天免疫系统的重要组成部分, 对细菌、真菌、原生生物和多种病原体都具有直接的抗菌活性^[54-56]。此外, HDPs 还具有强大免疫调节活性, 可以抑制炎症反应和促进伤口愈合^[57-60]。例如含有猪宿主防御肽 (PR-39/pBD-1) 的重组质粒可调节仔猪肠道的先天性和适应性免疫反应, 可以降低仔猪的腹泻率^[61]。

近年的研究表明, MCFAs 可以诱导人和动物体内 HDPs 的表达。国外 ZENG 等报道认为, 碳链长度为 3—10 的脂肪酸 (包含奇数碳和偶数碳) 能显著诱导体外培养的猪肠上皮细胞中至少 3 种防御素基因的表达, 但其诱导机制和动物体内效应不得而知^[62]; 这些脂肪酸也能诱导鸡巨噬细胞和单核细胞中防御素基因的表达^[10]。JIANG 等也报道, 短链、中链、长链脂肪酸都能不同程度地诱导人体内抗菌肽 LL-37 基因和蛋白的表达^[63]。WANG 等在探索辛酸 (C8) 和癸酸 (C9) 对肠上皮屏障功能的影响时, 发现辛酸 (C8) 和癸酸 (C9) 可促使内源性防御肽 pBD-1、pBD-2 的表达显著升高, 其作用机制为辛酸 (C8) 和癸酸 (C9) 减弱了经典组蛋白脱乙酰基酶途径的活性, 促进了启动子 pBD-1 和 pBD-2 上组蛋白 3 赖氨酸 9 (H3K9) 的乙酰化, 从而增强了 PBD-1 和 PBD-2 基因表达^[12]。基于 HDPs 在先天免疫和适应性免疫中的重要作用, 近来一些外源性的 HDPs 正在被开发和利用, 但体外合成的 HDPs 还存在稳定性较差、易在动物消化道及胃中发生降解的问题^[64]。BECHINGER 等^[65]和 CHEUNG 等^[66]报道指出使用外源 HDPs 成本较高且仍然存在耐药风险, 并且还可能影响内源性 HDPs 在先天性免疫中的保护功能。所以通过 MCFAs 调控内源性 HDPs 的合成与分泌已成为一种用于疾病控制和预防的有前途的抗生素替代方法^[67]。

4 中链脂肪酸不同于长链脂肪酸的消化、吸收和代谢特点

MCFAs 水解能力和吸收速度是长链脂肪酸 (Long Chain Fatty Acids, LCFAs) 的 6 倍, 代谢速度是其 10 倍, 能够快速为肠细胞和肝代谢提供能量^[3, 68]。利用同位素标记技术比较仔猪对中链脂肪酸和长链脂肪酸的吸收效果和氧化效果, 结果表明辛酸的吸收和氧化速率要显著高于油酸^[69]。其主要原因是 MCFAs 比 LCFAs 分子量小、呈极性且水溶性较好, 对胆盐和胰酶的依赖性低, 更容易被水解和吸收; MCFAs 吸收后不依赖肉毒碱的转运, 主要以游离形式进入门静脉, 能够自由通过线粒体的双层膜进入线粒体氧化, 进而快速为机体供能, 而 LCFAs 必须与肠细胞中的脂肪酸结合蛋白 (FABP) 结合, 转运到滑面内质网, 重新酯化形成甘油三酯, 然后与载脂蛋白结合形成乳糜微粒, 进入到淋巴系统, 通过血液循环

环被运往机体肌肉、肝脏、脂肪组织细胞^[68,70]。体外研究表明,中链脂肪酸可以显著提高肝细胞氧气的消耗量、NAD(P)H 的水平^[71]及氧化丙酮和乳酸的活性^[70]。用葵酸(C10)或月桂酸(C12)处理的 C2C12 肌管产生的 ROS 要显著低于肉豆蔻酸或棕榈酸处理组,且耗氧量比肉豆蔻酸(C14)或棕榈酸(C16)处理组高^[72]。喂食 MCFA 的小鼠肌细胞比 LCFAs 组线粒体氧化能力显著增强,活性氧自由基的产生显著降低^[73-74],这与体外研究结果一致。对其机理的解释方面,喂食 MCFA 的小鼠试验表明,MCFA 会诱导 ω 氧化基因 Cyp4a10 和 Cyp4a14 的表达,增加二羧基脂肪酸的产量,激活过氧化物酶体增殖物激活受体(peroxisome proliferators-activated receptors, PPARs),进而激活脂肪酸在微体中的 ω 氧化途径、在线粒体和过氧化物酶体中的 β 氧化途径,从而加速 MCFA 的氧化供能水平^[74]。由此可见,MCFA 在体内具有消化吸收快、代谢快、产生活性氧自由基少的特点,特别适合幼龄动物肠代谢和肝代谢所需的快速能量供应特点。

5 中链脂肪酸对仔猪存活率、生长性能、营养物质表观消化率和肠道微生物的影响

MCFA 在新生或断奶仔猪的研究报道较多^[75],在母猪、蛋鸡、肉鸡、牛饲料中也有一些零星报道^[76-79]。这些研究表明,MCFA 及其甘油酯可以调节畜禽营养代谢、提高畜产品品质,在动物生产中使用 MCFA 是发展绿色畜产品生产的有效途径之一。前人关于中链脂肪酸的添加浓度和形式以及对仔猪存活率、生长性能、营养物质表观消化率和肠道微生物的影响的研究在表 1 中进行了总结。

HANCZAKOWSKA 等基于 252 头新生仔猪的试验结果表明,日粮中添加 0.1% ($1\text{g}\cdot\text{kg}^{-1}$) 的辛酸(C8)或葵酸(C10)可使 84 日龄体重增加 14%—22%,平均日增重增加 15%—23%,料肉比降低 20%—30%,粗蛋白或粗脂肪的表观消化率提高 5%,粗纤维的表观消化率提高 10%—13%,死亡率下降 8.2%—11.3%,无氮浸出物的表观消化率变化不显著;同时,添加 0.1% 的辛酸(C8)或葵酸(C10)也都使肠绒毛高度、隐窝深度、及绒毛高/隐窝深度比值显著增加,有害菌产气荚膜梭菌的数量显著减少,葵酸的效应

更显著^[80]。在断奶仔猪饲料中添加 0.1% 的中链脂肪酸和植物精油复合物(桉树油+辛酸+葵酸),显著提高了仔猪日增重和采食量,并且与抗生素组、ZnO 组没有差异,同时也提高了干物质、粗蛋白、钙、磷、能量和氨基酸消化率^[81]。HANCZAKOWSKA 等基于 326 头断奶仔猪试验,在酸化剂(0.5% 的甲酸和丙酸)的基础上再添加 0.2% 的辛酸(C8)或葵酸(C10)可以进一步提高 84 日龄体重和平均日增重,进一步降低料肉比,粗纤维表观消化率进一步提高 11%—14% (干物质、粗蛋白、粗脂肪消化率也有提高)^[82]。0.3% 的中链脂肪酸和有机酸混合物(MCFA + 甲酸钙+乳酸钙+柠檬酸)可以替代仔猪日粮中的氧化锌,显著提高仔猪采食量、促进动物生长,同时还可以显著增加直肠和回肠中乳酸杆菌的数量并显著降低沙门氏菌和肠球菌数量^[83]。而日粮中添加高浓度(8%)的中链脂肪酸(60%辛酸和 40%葵酸)可以提高饲料转化效率和氨基酸的消化率,但差异不显著。

综上所述,高浓度(8%)的中链脂肪酸可以提高饲料的转化效率以及能量和氨基酸的消化率,但差异不显著。低浓度(0.1%—0.5%)的中链脂肪酸可显著提高新生或断奶仔猪存活率、营养物质消化率、饲料转化率、改善肠道健康,促进生长。中链脂肪酸对生长性能提升效果较好的为辛酸(C8)和葵酸(C10)。体外抗菌效果方面,0.002% 的葵酸和 0.0015% 的柠檬酸组合对 *E.coli* O157:H7 的杀菌能力最强,0.004% 葵酸和 0.006% β -间苯二酸组合对 *E.coli* O157:H7 的杀菌能力最强^[33-34]。体内应用效果方面,0.1% 的桉树油-辛酸-葵酸组成的复合物、0.3% 的 MCFA-甲酸钙-乳酸钙-柠檬酸组成的复合物和 0.2% 的中链脂肪酸(辛酸或葵酸)与 0.5% 的有机酸(甲酸和丙酸)组成的复合物均可以达到替代仔猪饲料中氧化锌的作用。不同的动物或相同动物的不同生长阶段,以及养殖场管理方式和环境等都是影响中链脂肪酸组合效果的重要因素,特别是不同的养殖场对组合效应的报道结果缺乏一致性,这可能是不同养殖场的不同管理和环境导致的。

6 微囊化技术是提高中链脂肪酸溶解度和生物利用度,避免难闻气味的有效方法

微囊化技术是将小的固体颗粒,液滴或气体包裹

表 1 基础仔猪日粮中添加一定浓度的中链脂肪酸对仔猪生产性能、营养物质表观消化率、肠道微生物及结构和仔猪死亡率的影响

Table 1 Effects of the addition of a certain concentration of medium chain fatty acids to the basal piglet diet on piglet performance, nutrient apparent digestibility, intestinal microbe and structure, and piglet mortality

添加浓度和形式 Concentration and form	生长性能 Growth performance	营养物质表观消化率 The apparent digestibility of nutrients	肠道菌群及结构 Intestinal flora and structure	仔猪死亡率 Piglet mortality	参考文献 References
8%中链脂肪酸(60%辛酸+40%癸酸) 8% MCFA (60% Caprylic acid + 40% Decanoic acid)	饲料转化效率升高 Feed conversion efficiency decreased	能量和氨基酸消化率提高 ($P>0.05$) The digestibility of energy and amino was improved. ($P>0.05$)	——	——	[84]
0.2%中链脂肪酸(辛酸或癸酸或辛酸+癸酸) 0.2% MCFA (Caprylic acid or Decanoic acid or Caprylic acid + Decanoic acid)	平均日增重显著增加 ($P<0.01$); 饲料转化效率提高 ($P>0.05$) The ADG was increased significantly ($P<0.01$) and the FCR was improved ($P>0.05$)	粗蛋白 ($P<0.01$) 和粗纤维 ($P<0.05$) 消化率显著提高 The digestibility of crude protein and crude fiber increased significantly. Crude protein ($P<0.01$); Crude fiber ($P<0.05$)	产气荚膜梭菌的数量显著降低 ($P<0.01$); 绒毛高度和隐窝深度增加, 癸酸组达到显著 ($P<0.01$) The number of clostridium perfringens was decreased significantly ($P<0.01$). The height of villi and the depth of crypt was increased, the Decanoic acid group reached a significant level	死亡率下降 8.2%-11.3% Mortality was reduced by 9.1% to 18.7%	[80]
0.1%微囊化的桉树中链脂肪酸(桉树油+辛酸+癸酸) 0.1% E-MCFA (Eucalyptus oil + Caprylic acid + Decanoic acid)	平均日增重和平均日采食量显著增加 ($P<0.05$) ADG and ADFI were significantly increased ($P<0.05$)	蛋白质、钙、磷和氨基酸的消化率显著增加 ($P<0.05$) The digestibility of protein, calcium, phosphorus and amino acids was increased significantly ($P<0.05$)	——	——	[81]
0.2%中链脂肪酸(辛酸或癸酸)+0.5%酸化剂(甲酸+丙酸) 0.2% MCFA (Caprylic acid or Decanoic acid) + 0.5% acidifier (Formic acid + Propionic acid)	体重和平均日增重显著增加 ($P<0.05$); 饲料转化效率升高, 在 35-56d 差异显著 ($P<0.5$) The BW and the ADG were increased significantly. ($P<0.05$) FCR increased, and the difference was significant from 35 to 56d ($P<0.5$)	蛋白质、脂肪和粗纤维的消化率显著提高 ($P<0.05$) The digestibility of protein, fat and crude fiber was significantly improved ($P<0.05$)	产气荚膜梭菌数量降低; 绒毛高度显著增加 ($P<0.05$) The number of clostridium perfringens and the height of villi were significantly increased ($P<0.05$)	——	[82]
0.2%中链脂肪酸(辛酸或癸酸)+0.5%酸化剂(甲酸+丙酸) 0.2% MCFA (Caprylic acid or Decanoic acid) + 0.5% acidifier (Formic acid + Propionic acid)	体重和平均日增重显著增加 ($P<0.05$); 饲料转化效率升高, 在 35-56d 差异显著 ($P<0.5$) The BW and the ADG were increased significantly. ($P<0.05$) FCR increased, and the difference was significant from 35 to 56d ($P<0.5$)	蛋白质、脂肪和粗纤维的消化率显著提高 ($P<0.05$) The digestibility of protein, fat and crude fiber was significantly improved ($P<0.05$)	产气荚膜梭菌数量降低; 绒毛高度显著增加 ($P<0.05$) The number of clostridium perfringens and the height of villi were significantly increased. ($P<0.05$)	——	[82]
0.3%混合物(MCFA+甲酸钙+乳酸钙+柠檬酸) 0.3% mixture (MCFA + Calcium formate + Calcium lactate + Citric acid)	平均日采食量显著增加 ($P<0.05$); 平均日增重, 饲料转化效率增加 ($P>0.05$) The ADFI was increased significantly ($P<0.05$), the ADG and the FCR were increased. ($P>0.05$)	氨基酸利用率显著提高 ($P<0.01$) The amino acid utilization rate was improved significantly ($P<0.01$)	直肠和回肠中乳酸杆菌的数量显著增加 ($P<0.05$) The number of lactobacillus in the rectum and ileum significantly increased ($P<0.05$)	——	[83]
0.2%MCFA(己酸+辛酸+癸酸+月桂酸)+0.01%粪肠球菌 0.2%MCFA (Caproic acid + Octanoic acid + Decanoic acid + Lauric acid) + 0.01% <i>Enterococcus faecalis</i>	平均日增重和饲料转化效率显著提高 ($P<0.05$)。 The ADG and FCR were significantly improved ($P<0.05$)	干物质、氮、能量的消化率提高 ($P>0.05$) The digestibility of DM, nitrogen, and energy was increased	对肠道菌群没有影响 No effect on intestinal flora.	——	[85]
0.3%癸酸(或辛酸)+饲料粪肠球菌(0.35×10^9 CFU/kg 饲料) 0.3% Decanoic Acid (or Capric acid) + <i>Enterococcus faecalis</i> (0.35×10^9 CFU/kg feed)	体重和平均日增重显著提高; 癸酸 ($P<0.01$); 辛酸 ($P<0.05$)。 The BW and ADG were significantly improved. Maleic acid ($P<0.01$); Poignancy ($P<0.05$).	——	盲肠和空肠中大肠杆菌和产气荚膜梭菌数量显著降低 ($P<0.05$); 十二指肠的绒毛高度和隐窝深度显著增加 ($P<0.01$) The numbers of <i>E. coli</i> and <i>Clostridium perfringens</i> in cecum and jejunum were significantly reduced. ($P<0.05$) The villi height and crypt depth of duodenum were significantly increased ($P<0.01$)	死亡率下降 2.2%-4.5% Mortality was reduced by 2.2% to 4.5%	[79]
0.5%的中链脂肪酸(己酸或辛酸或癸酸) 0.5% MCFA (Caproic acid or Caprylic acid or Decanoic acid)	平均日增重和饲料转化效率提高; 癸酸 ($P<0.05$); 己酸和辛酸组 ($P>0.05$) The ADG and FCR were increased. Keiroic acid ($P<0.01$); Caproic acid or Caprylic acid ($P>0.05$)	——	1.5%MCFA 混合物对肠道菌群没有影响 The 1.5% MCFA mixture had no effect on intestinal flora.	——	[86]

BW: 体重; FCR: 饲料转化率; ADFI: 平均日采食量; ADG: 平均日增重; DM: 干物质

BW: weight; FCR: feed conversion rate; ADFI: average daily food intake; ADG: average daily weight gain; DM: Dry matter

在涂层中的一种技术,已经被用于食品工业、化妆品及制药等多个领域,它可以保护活性成分免受外部环境的影响,掩盖难闻的气味,还可以将活性成分运送到动物体内特定的作用靶点^[87]。MCFAs 难溶于水、有难闻气味、刺激缩胆囊素释放而减少采食量^[3]。MCFAs 浓度随着胃肠道逐渐降低,在仔猪日粮中添加包被的中链脂肪酸,中链脂肪酸在胃肠道各部位的浓度显著高于对照组(添加相同浓度的未包被中链脂肪酸)^[88],这表明利用包被技术减少中链脂肪酸的用量及延长中链脂肪酸在胃肠道的作用时间的可行性,将有利于降低仔猪的腹泻率。中链脂肪酸和有机酸或精油具有协同抗菌作用,在断奶仔猪饲料中添加中链脂肪酸和植物精油复合物制成的微囊可以达到替代日粮中氧化锌和抗生素的作用^[82]。体外胃肠道模拟试验表明,月桂酸和百里香酚制成的微粒可以被运输到肠道后段以防止断奶仔猪腹泻^[89]。日粮中添加有机酸和中链脂肪酸制成的脂质微囊,显著提高了生长猪的生产性能^[90]。目前国内鲜有关于包被中链脂肪酸用作饲料添加剂替代抗生素的报道。

7 小结

中链脂肪酸是哺乳动物母乳、皮肤、粘膜先天防御系统的重要组成部分,中链脂肪酸诱导人、猪和鸡内源性防御肽表达现象的发现,是对已有中链脂肪酸体外抗菌功能认知的有益补充,这些新功能将促进中链脂肪酸在仔猪饲料抗生素替代品开发中的应用。日粮中添加低浓度(0.1%—0.5%)的中链脂肪酸可提高新生或断奶仔猪存活率、营养物质消化率、饲料转化率,改善肠道健康,促进仔猪生长。中链脂肪酸与植物精油或有机酸具有协同抗菌增效功能,将其混合制备成微囊颗粒,能很好地提高其溶解性,避免难闻气味,提高生物利用度。

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