



运输应激导致牛生理系统失衡的研究进展

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摘 要: 运输应激是影响牛健康和生产性能的重要因素, 涉及其代谢、消化、内分泌、免疫等多个生理系统。在运输过程中, 多种应激源(如禁食、缺水、温度波动、拥挤、装卸等)会对牛生理机能造成负面影响, 引起应激激素大量产生和瘤胃微生物群落丰度改变, 进而降低免疫功能和抗氧化能力, 造成组织器官损伤, 最终影响整体健康和生产性能。本文综述了运输应激引起牛机体生理失衡的变化机制, 以期明确牛运输应激防控靶点和提高牛运输过程中的动物福利提供理论参考。

关键词: 运输应激; 牛; 代谢; 免疫; 内分泌

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Research Progress on Transport Stress-Induced Physiological Imbalance in Cattle

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Abstract: Transport stress is a significant factor affecting cattle health and production performance, involving disruptions in multiple physiological systems such as metabolism, digestion, endocrinology, and immunity. During transportation, various stressors (such as fasting, dehydration, temperature fluctuations, overcrowding, and loading/unloading) can negatively impact cattle physiological functions, leading to the excessive production of stress hormones and changes in rumen microbial community abundance. This, in turn, reduces immune function and antioxidant capacity, causes tissue and organ damage, and ultimately affects overall health and production performance. This review summarizes the mechanisms underlying physiological imbalances in cattle caused by transportation stress, aiming to provide theoretical references for identifying target points for controlling transportation stress in cattle and improving animal welfare during transportation.

Keywords: transport stress; cattle; metabolism; immunity; endocrine

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牛的运输是现代畜牧生产中重要环节。然而,运输过程中的多重应激源(如禁食、缺水、温度变化、噪音、装卸、拥挤、颠簸等)会引发牛产生运输应激反应,导致代谢紊乱、消化功能障碍、内分泌失调、免疫抑制和氧化应激等一系列负面影响,影响其整体健康和生产性能^[1]。近年来,随着现代畜牧业集约化发展,运输应激对牛健康和养殖效益的影响已引起学术界和产业界广泛重视。研究表明,运输过程中常发生免疫抑制^[2]、代谢紊乱和氧化应激^[3]等病理反应,导致生产性能下降和动物福利受损。目前主要通过优化运输条件(包括温湿度控制、减噪、限制运输时间及调整装载密度等)^[4-5]、建立基于生物传感技术的实时监测系统^[4-5]等措施缓解运输应激。然而,目前对于多应激源交互作用研究仍显不足,本综述旨在从系统生物学角度,聚焦内分泌-免疫-消化调控轴,系统阐述运输应激对牛机体多种生理系统的作用机制,以期探明牛运输应激防控靶点,为缓解运输应激、提高运输过程中牛的动物福利提供理论依据。

1 复合性应激源对牛机体代谢稳态的破坏

1.1 摄食减少导致代谢紊乱

牛群运输过程中,由于受应激源刺激,代谢和免疫功能受到显著影响。研究表明,牛在运输期间采食量显著下降,甚至停止,且体重随运输时间延长而明显降低^[6-8]。其原因在于营养缺乏的状态下,体内葡萄糖供应减少,肝糖原消耗加剧,血糖水平降低^[9];低血糖导致胰高血糖素分泌增多,进一步刺激肝脏糖异生和脂肪分解,以提供能量补充^[10]。然而,此状态下血清游离脂肪酸和甘油显著增加,加重代谢负担^[11],引起代谢紊乱,进一步诱发体内皮质醇(cortisol, COR)和多种促炎细胞因子分泌增多,免疫球蛋白含量下降,导致免疫力削弱和炎症反应加剧^[12-13]。因此,摄食减少会引发一系列代谢和免疫功能的紊乱,甚至导致亚临床酮病^[14]。

1.2 空间压迫导致的代谢负荷加剧

不同动物体之间在自然条件下会保持一定距离,而运输过程中,牛在较高的拥挤密度下进行转运,这无疑会对牛生理和心理均造成巨大影响。研究表明,将9月龄公牛以 $1.27\text{ m}^2\cdot\text{头}^{-1}$ 装载密度进行运输,其非酯化脂肪酸(non-esterified fatty acids, NEFA)含量显著高于不运输的牛,说明运输显著提升牛的代谢负荷^[15];同时高密度装载会导致牛心率

和呼吸频率升高,激活机体交感神经系统并造成持续应激状态^[16]。装卸过程中的空间限制、坡道变化和驱赶压力也会显著激发牛的应激反应。装卸阶段,牛面临空间和环境的改变,导致COR和肾上腺素浓度急剧升高,引起心率加快和体温上升,但运输过程中,体内激素长时间维持在高水平会抑制免疫功能,从而增加疾病感染的风险^[3]。研究表明,高温环境下的装卸极易引发氧化应激,组织损伤和脱水等问题,对牛的生理稳态造成额外负担^[17]。此外,不当的装卸操作会对牛机体造成创伤和瘀伤,影响肉质品质和健康状况,尤其是在屠宰前的装卸阶段更为明显^[18]。因此,优化装卸环境、减少噪音和恐惧因素可有效缓解装卸应激反应,提升牛的健康状态和运输适应性^[18-19]。

1.3 温度变化剧烈造成的代谢失衡

牛汗腺不发达,在高温环境下难以通过出汗散热,尤其在运输过程中,瘤胃发酵产热和拥挤等导致体温调节障碍,更易引起热应激的发生,引发多重生理功能障碍^[20]。在高温环境下,牛体内活性氧(reactive oxygen species, ROS)产生显著增加,超出抗氧化酶系统的清除能力,导致ROS在细胞内累积^[21],损伤线粒体膜结构,影响线粒体呼吸链功能,引起ATP合成减少,导致细胞能量供应不足,进而加剧细胞损伤^[22]。为应对能量水平下降,机体在ATP缺乏的情况下会大量分解脂肪,产生的游离脂肪酸可加重肝脏代谢负担,极易造成机体代谢失衡。在热应激状态下,牛肝脏细胞线粒体功能显著下降,氧化损伤加剧^[23]。此外,热应激引发的促炎因子水平升高加剧炎症反应,影响肝脏和肾脏的功能,抑制免疫功能并进一步紊乱代谢稳态^[21]。值得注意的是,上述应激源并非孤立存在。当禁食缺水与高温环境叠加时,会加剧代谢失衡;而高密度装载与频繁装卸的组合则可能放大神经系统的激活,使得应激带来的损伤扩大。这种复合应激源的协同作用会引发内分泌系统、免疫系统和消化系统的级联反应,最终导致牛机体生理功能全面失衡。

2 运输应激导致牛机体内分泌系统失衡

在运输过程中,各种应激源通过刺激机体的神经-内分泌-免疫反应轴,破坏机体稳态,引发生理功能紊乱并导致应激性损伤^[24]。面对多重应激源刺激时,机体通过交感-肾上腺髓质轴(sympathetic nervous system-adrenal medulla axis, SAM)和下丘

脑-垂体-肾上腺皮质轴(hypothalamic-pituitary-adrenal cortical axis, HPA)共同对抗应激^[2]。SAM轴通过刺激肾上腺髓质增加儿茶酚胺(catecholamine, CA)的合成与释放^[25],引发心率加快、血压升高等机体反应,缓解牛在短时间适应环境压力;但长期高水

平CA状态,将会在一定程度上导致体内ROS增多以及免疫细胞活性下降。HPA轴则主要负责调控长期应激^[26],通过释放糖皮质激素调节机体代谢、免疫和炎症反应(图1)。

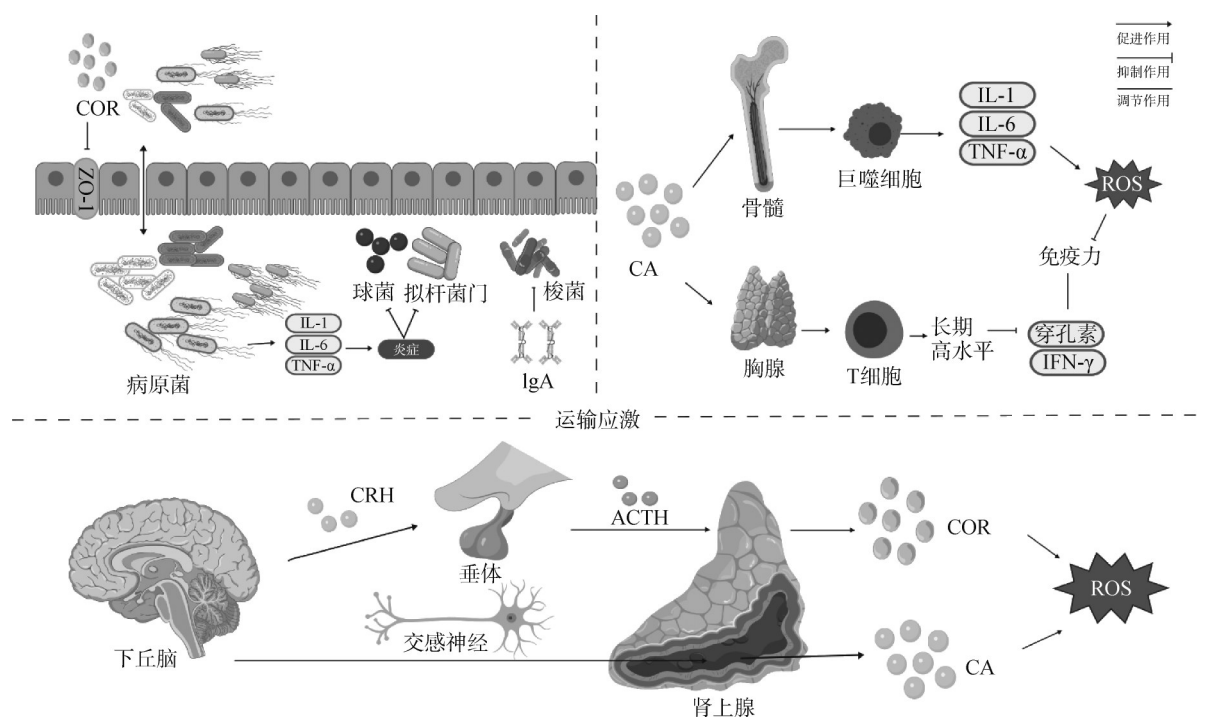


图1 运输应激导致牛机体多生理系统紊乱示意图(自制)

Fig. 1 Schematic diagram of multiple physiological system disorders caused by transport stress in cattle (author drawing)

COR是应激中最主要的糖皮质激素之一,对应激反应有关键调节作用^[27]。正常生理状态下,一定浓度的COR可抑制过度炎症反应和消肿^[21],保护组织免受应激性损伤,并能在应激条件下促进碳水化合物、脂肪和蛋白质的代谢,为机体提供必要的能量^[28]。然而,在运输应激持续作用下,HPA轴的过度激活会导致机体COR含量持续维持在高水平,引发免疫抑制^[16]。研究表明,高水平COR通过抑制促炎细胞因子的释放和降低免疫细胞的活性,可显著降低机体抗病能力^[29]。长途运输后牛血清COR含量显著升高,炎症标志物浓度升高,同时免疫球蛋白水平显著下降^[8],表明运输应激对免疫功能的抑制作用。运输应激导致的COR水平持续升高是多个器官损伤的核心驱动因素,高水平COR诱导的氧化应激可加重脂质过氧化反应,直接损伤肝脏和肾脏功能,削弱其代谢和排毒能力^[23];同时COR还可通过降低空肠紧密连接蛋白Claudin-1、Occludin、ZO-1表达,增加肠黏膜的通透性^[30],从而使得病原

菌更易入侵机体。在COR的作用下,牛体内NEFA水平显著升高,同时肝功能标志物的表达发生明显改变,表明代谢负担和肝脏功能受损是运输应激下高COR介导的机体损伤^[31]。此外,运输应激对心血管系统的损害也不可忽视,COR水平长时间维持在高水平可能对心肌造成不可逆的损伤,导致机体供血能力下降,并诱发慢性炎症反应,进一步削弱机体免疫功能^[16]。与此同时,在运输过程中,机体所大量释放的糖皮质激素和儿茶酚胺通过增加脂肪分解酶的表达水平从而促进脂肪分解^[32];脂肪分解产物NEFA进入肝脏并用于糖异生,这一过程中需要更多的氧气和能量,同时伴随更多的ROS产生^[33],大量自由基与氧气反应形成过氧化产物,损伤细胞大分子(如脂质、蛋白质和DNA等),最终引起组织和器官损伤,造成机体氧化应激。此外,脂肪分解产生的游离脂肪酸和多不饱和脂肪酸氧化后形成的中间产物会进一步促进细胞氧化损伤^[34]。

综上,运输应激通过激活神经-内分泌轴调节短

期和长期应激反应。然而,持续的高强度应激会导致代谢失衡、免疫抑制、氧化损伤和器官功能障碍,增加牛的健康风险并降低其生产性能。

3 运输应激致使牛机体免疫力下降

运输应激通过复杂的生理通路对牛的免疫系统产生影响,包括先天免疫和适应性免疫的动态调控。先天免疫作为机体第一道防线^[35],在应激条件下迅速启动,通过 NF- κ B (nuclear factor kappa-B, NF- κ B) 信号通路激活促炎因子如白细胞介素-1 (interleukin-1, IL-1)、白细胞介素-6 (interleukin-6, IL-6)、肿瘤坏死因子- α (tumor necrosis factor- α , TNF- α) 表达^[36]。这些促炎因子不仅直接触发炎症,还通过调控免疫细胞的分化进一步增强炎症反应^[23]。适应性免疫系统则需要更长时间激活,长期的应激状态会导致 T 细胞逐渐出现免疫衰竭表型,表现为抑制性受体表达增加,穿孔素分泌减少,细胞毒活性下降,导致特异性免疫应答减弱^[37],从而降低机体对病原的抵抗能力(图 1)。在运输过程中,由于无法及时获得饲料补充,机体转而调动脂肪作为能量的主要来源,脂肪被大量分解导致血清中 NEFA 和甘油浓度上升^[38]。这一过程中,细胞线粒体负担加重,生成的 ROS 显著增多,不仅加重代谢损伤,还通过与免疫系统相互作用,刺激促炎细胞因子分泌,导致免疫系统的激活和炎症反应的加剧^[39]。此外,NEFA 还可通过 NF- κ B 信号转导通路促进急性期蛋白 (acute phase proteins, APP) 以及其他炎症介质的表达^[39-40],这些促炎细胞因子和 APP 共同构成运输应激的主要炎症调节网络,在短期内增强机体防御功能^[36]。然而,NF- κ B 信号通路的长时间激活将会导致免疫细胞持续受到响应,从而失去对免疫应答的敏感性,引发机体慢性炎症和免疫耐受,干扰免疫平衡^[16]。

APP 是牛运输应激重要生物标志物^[8],其合成受到 NF- κ B 通路以及促炎细胞因子直接调控^[28]。在应激条件下,机体释放糖皮质激素和儿茶酚胺类物质,促进细胞因子生成^[41],这些细胞因子通过结合肝细胞表面受体,显著促进 APP 合成^[42],进而增强炎症反应^[43]。研究表明,APP 水平显著升高短期内有助于组织修复和炎症控制,但长期升高可能引发慢性免疫负担^[44],造成免疫系统持续激活和能量过度消耗,导致抗病力下降、免疫球蛋白水平降低及特异性免疫功能受损^[36,39]。运输中 NEFA 和

APP 过度分泌均会导致机体炎症的发生^[39,45]。从机体角度而言,炎症反应的启动始于巨噬细胞识别内源性危险信号或细胞内病原体^[46]。巨噬细胞识别并应对体内危险信号或感染^[47],通过分泌趋化因子和细胞因子募集其他免疫细胞并进行激活^[48-49],从而触发炎症级联反应。在这一过程中,烟酰胺腺嘌呤二核苷酸磷酸氧化酶 (NADPH oxidase, NOX) 被激活^[50],该酶使用来自细胞内 NADPH (nicotinamide adenine dinucleotide phosphate, NADPH) 的电子,将细胞外 O_2 还原为 $O_2^{\cdot-}$ ^[51],产生大量的 ROS,打破氧化-抗氧化平衡并加剧氧化损伤。巨噬细胞在免疫应答中产生的 ROS 不仅用于清除病原体,还参与炎症信号传递,这一过程提示,炎性反应极易导致氧化应激,而氧化损伤可能削弱机体免疫功能,形成免疫抑制的恶性循环。在免疫抑制情况下,机体呼吸器官的纤毛-黏液排送系统无法有效发挥作用,黏液中免疫球蛋白等免疫活性物质含量减少^[39],病原体清除能力下降,导致支气管肺炎的发生,造成机体损伤^[52]。

综上所述,牛在运输过程中,由于持续的应激激活 NF- κ B 通路,导致促炎细胞因子(如 IL-1、IL-6 和 TNF- α)大量释放并引发 APP 水平上升,表明机体处于急性应激状态^[8,35]。然而,持续的炎症反应可能带来慢性免疫负担,干扰免疫平衡^[44,53]。这种动态免疫反应说明运输应激不仅影响牛的早期机体防御,还会对长期的免疫稳定性造成影响。

4 运输应激降低牛机体消化系统功能

瘤胃是反刍动物特有的消化器官,其正常功能是牛健康生产的基础。然而在运输过程中,各种应激源的刺激,导致牛食欲减退,甚至废绝,打破反刍行为的规律性,从而引发瘤胃 pH 和挥发性脂肪酸浓度发生显著变化。研究发现,运输应激导致牛瘤胃中乙酸、丙酸和丁酸浓度增加,乙酸与丙酸比值上升^[36,54];这种脂肪酸含量与比例的变化表明瘤胃发酵模式的转变,能量利用率降低^[55]。瘤胃内 pH 过高或者过低均会干扰瘤胃代谢平衡,并且抑制纤维分解菌和淀粉分解菌的活性,进一步降低能量利用率^[56]。

运输应激可改变肠道免疫状态从而影响肠道菌群(图 1)。在正常生理状态下,机体免疫系统始终对肠道菌群起到“监视”和清除作用^[57];肠道分泌型 IgA 可与肠道病原微生物结合以便于机体的清

除,但应激所造成的免疫抑制是肠道菌群紊乱的原因之一^[58]。研究表明,IgA 的缺乏可能使得肠道厌氧菌(如分节丝状菌)大量繁殖^[59],高水平的分节丝状菌又会扰乱肠道免疫平衡,引发恶性循环^[60];另一项研究表明,在 IgA 缺陷小鼠中,空肠菌群结构发生明显变化,表现为梭菌科含量降低,副球菌属含量升高^[61]。在牛运输中,拟杆菌门、厚壁菌门、黏胶球形菌门等是受运输因素影响最大的菌群,对维持机体消化和整体代谢具有关键作用^[13,36]。在应激状态下,黄牛瘤胃拟杆菌门丰度从 78.43% 降至 73.47%^[36],而拟杆菌作为纤维素主要降解者,其丰度下降直接导致瘤胃植物多糖分解效率降低,促使机体动员自身脂肪分解以满足能量需求。这种脂肪动员产生的脂肪酸进一步改变瘤胃 pH,pH 的改变又会促使菌群丰度变化,形成恶性循环,加剧机体代谢紊乱。厚壁菌门同样至关重要,其不仅能分解碳水化合物和纤维素,生成短链脂肪酸以提供能量,还能通过产生酸性代谢产物来调节瘤胃 pH,为有益菌群提供适宜的生存环境^[62]。犊牛在运输后 72 h,厚壁菌门丰度出现下降,同时梭杆菌门丰度显著下降,这一变化导致机体生态失调和代谢失调^[63]。而瘤胃球菌是瘤胃主要微生物群,以其出色的溶糖能力和高效的纤维素降解作用而受到关注。Li 等^[64]研究发现,牛运输 16 h 后,瘤胃球菌属丰度显著下降,进一步证实了运输应激对微生物群落结构的负面影响。

运输过程中每一种与营养平衡相关的菌群丰度对调节机体营养和代谢均发挥重要作用,而一系列运输源的刺激会导致肠道菌群丰度减少,机体代谢平衡紊乱,引发组织器官产生氧化应激,削弱机体对病原的抵抗力,最终导致牛在运输过程受到全身性的损伤。

5 小结与展望

运输应激涉及消化系统、免疫系统、神经内分泌系统等多个生理系统,造成免疫系统应激、氧化应激和代谢紊乱,引发一系列生理损伤,并呈现显著的网络化特征:消化系统紊乱通过菌群-代谢轴影响免疫功能;内分泌失调通过激素-氧化损伤加剧组织损伤;而免疫抑制又反向加重代谢负担。这种多系统交互作用提示,有效的应激干预策略需要突破单一系统的局限,从系统生物学角度建立多方面调控体系。尽管目前已有研究探讨了运输应激对牛

免疫、代谢、内分泌、消化等方面的影响,但对于运输应激的动态机制、免疫调节机制以及长期免疫耐受效应等方面的研究仍需进一步深入。未来的研究可侧重于运输应激与内分泌系统及免疫系统相互作用的研究,探索更精确的应激评估方法,并开发有效的干预措施,以减少运输应激对牛的负面影响。

参考文献(References):

- [1] HU W, YE T, YANG Y, et al. Effects of transport stress on pathological injury and expression of main heat shock proteins in the caprine stomach[J]. *BMC Vet Res*, 2020, 16(1):347.
- [2] VAN ENGEN N K, COETZEE J F. Effects of transportation on cattle health and production: a review [J]. *Anim Health Res Rev*, 2018, 19(2):142-154.
- [3] NORBERT K, WAYNE L, CHARLES W, et al. Effect of transport stress on respiratory disease, serum antioxidant status, and serum concentrations of lipid peroxidation biomarkers in beef cattle [J]. *Am J Vet Res*, 2004, 65(6):860-864.
- [4] NIELSEN S S, ALVAREZ J, BICOUT D J, et al. Welfare of cattle during transport [J]. *Efsa J*, 2022, 20(9):e07442.
- [5] SWANSON J C, MORROW-TESCH J. Cattle transport: historical, research, and future perspectives [J]. *J Anim Sci*, 2001, 79(E-Suppl):E102.
- [6] CHEN Y, ARSENAULT R, NAPPER S, et al. Models and methods to investigate acute stress responses in cattle [J]. *Animals-Basel*, 2015, 5(4):1268-1295.
- [7] GONZALEZ L A, SCHWARTZKOPF-GENSWEIN K S, BRYAN M, et al. Factors affecting body weight loss during commercial long haul transport of cattle in north america [J]. *J Anim Sci*, 2012, 90(10):3630-3639.
- [8] ARTHINGTON J D, EICHERT S D, KUNKLE W E, et al. Effect of transportation and commingling on the acute-phase protein response, growth, and feed intake of newly weaned beef calves [J]. *J Anim Sci*, 2003, 81(5):1120-1125.
- [9] PARKER A J, DOBSON G P, FITZPATRICK L A. Physiological and metabolic effects of prophylactic treatment with the osmolytes glycerol and betaine on bos indicus steers during long duration transportation [J]. *J Anim Sci*, 2007, 85(11):2916-2923.

- [10] LI J, DANG P, LI Z, et al. Peroxisomal ERK mediates Akh/glucagon action and glycemic control [J]. *Cell Rep*, 2023, 42(10):113200.
- [11] MA Z, FANG L, UNGERFELD E, et al. Supplementation of rumen-protected glucose increased the risk of disturbance of hepatic metabolism in early postpartum holstein cows [J]. *Antioxidants-Basel*, 2022, 11(3):469.
- [12] 王莉梅, 王德宝, 赛音巴雅尔, 等. 运输应激对安格斯牛血液生理生化指标的影响[J]. 中国畜牧杂志, 2020, 56(5):167-170.
WANG L M, WANG D B, SAI Y B Y E, et al. Effect of transportation stress on blood physiological and biochemical indices in angus cattle[J]. *Chinese Journal of Animal Science*, 2020, 56(5):167-170. (in Chinese)
- [13] 彭浩宇. 远距离运输对西门塔尔牛主要临床指标、血液相关因子及肠道菌群的影响[D]. 成都: 四川农业大学, 2023.
PENG H Y. Effects of long-distance transportation on major clinical indicators, blood-related factors and intestinal flora in simmental cattle [D]. Chengdu: Sichuan Agricultural University 2023. (in Chinese)
- [14] 田 甜, 何基保, 李 雯, 等. 亚临床酮病奶牛肝脏脂质谱代谢组学变化对卵泡发育的影响[J]. 中国兽医杂志, 2023, 59(7):6-16.
TIAN T, HE J B, LI W, et al. Influence of changes in hepatic lipid metabolomics on follicular development in cows with subclinical ketosis [J]. *Chinese Journal of Veterinary Medicine*, 2023, 59(07):6-16. (in Chinese)
- [15] EARLEY B, O'RIORDAN E G. Effects of transporting bulls at different space allowances on physiological, haematological and immunological responses to a 12-h journey by road [J]. *Irish J Agr Food Res*, 2006, 45(1):39-50.
- [16] BURDICK N C, CARROLL J A, HULBERT L E, et al. Temperament influences endotoxin-induced changes in rectal temperature, sickness behavior, and plasma epinephrine concentrations in bulls [J]. *Innate Immun—London*, 2011, 17(4):355-364.
- [17] MINKA N S, AYO J O. Effects of loading behaviour and road transport stress on traumatic injuries in cattle transported by road during the hot-dry season [J]. *Livest Sci*, 2007, 107(1):91-95.
- [18] HUERTAS S M, KEMPENER R E A M, VAN EERDENBURG F J C M. Relationship between methods of loading and unloading, carcass bruising, and animal welfare in the transportation of extensively reared beef cattle[J]. *Animals-Basel*, 2018, 8(7):119.
- [19] ENIOLORUNDA O O, FASHINA O E, ARO O O. Adaptive physiological response to load time stress during transportation of cattle in nigeria [J]. *Archivos De Zootecnia*, 2009, 58(222):223-230
- [20] WANG Y, YANG C, ELSHEIKH N A H, et al. HO-1 reduces heat stress-induced apoptosis in bovine granulosa cells by suppressing oxidative stress [J]. *Aging (Albany, NY.)*, 2019, 11(15):5535-5547.
- [21] BELHADJ SLIMEN I, NAJAR T, GHARAM A, et al. Heat stress effects on livestock; molecular, cellular and metabolic aspects, a review [J]. *J Anim Physiol An N*, 2016, 100(3):401-412.
- [22] LI D, DING Z, DU K, et al. Reactive oxygen species as a link between antioxidant pathways and autophagy [J]. *Oxid Med Cell Longev*, 2021, 2021:5583215.
- [23] GUO Z, GAO S, OUYANG J, et al. Impacts of heat stress-induced oxidative stress on the milk protein biosynthesis of dairy cows [J]. *Animals-Basel*, 2021, 11(3):726.
- [24] 夏传齐, 白萨茹拉, 马 慧, 等. 犊牛运输应激的研究进展[J]. 中国畜牧杂志, 2023, 59(11):37-42.
XIA C Q, BAI S R L, MA H, et al. Research progress on transport stress of calves [J]. *Chinese Journal of Animal Science*, 2023, 59(11):37-42. (in Chinese)
- [25] MITCHELL G, HATTINGH J, GANHAO M. Stress in cattle assessed after handling, after transport and after slaughter [J]. *Vet Rec*, 1988, 123(8):201-205.
- [26] PULOPULOS M M, BAEKEN C, De RAEDT R. Cortisol response to stress: The role of expectancy and anticipatory stress regulation [J]. *Horm Behav*, 2020, 117:104587.
- [27] LIGHTMAN S L, BIRNIE M T, CONWAY-CAMPBELL B L. Dynamics of ACTH and cortisol secretion and implications for disease [J]. *Endocr Rev*, 2020, 41(3):BNA002
- [28] EARLEY B, BUCKHAM SPORER K, GUPTA S. Invited review: relationship between cattle transport, immunity and respiratory disease [J]. *Animal*, 2017, 11(3):486-492.
- [29] MOSHAGE H. Cytokines and the hepatic acute phase response [J]. *J Pathol*, 1997, 181(3):257-266.
- [30] ZHENG G, WU S, HU Y, et al. Corticosterone mediates stress-related increased intestinal permeability in a region-specific manner [J]. *Neurogastroent Motil*, 2013, 25(2):e127-e139.

- [31] SANTINELLO M, LORA I, VILLOT C, et al. Metabolic profile of charolais young bulls transported over long-distance [J]. *Prev Vet Med*, 2024, 231: 106296.
- [32] 徐 冲, 徐国恒. 糖皮质激素与脂肪代谢和胰岛素抵抗[J]. 生理科学进展, 2009, 40(1): 19-23.
XU C, XU G H. Glucocorticoids and fat metabolism and insulin resistance [J]. *Progress in Physiological Sciences*, 2009, 40(1): 19-23. (in Chinese)
- [33] KOWALSKA M, PIEKUT T, PRENDECKI M, et al. Mitochondrial and nuclear DNA oxidative damage in physiological and pathological aging [J]. *Dna Cell Biol*, 2020, 39(8): 1410-1420.
- [34] SCHONFELD P, WOJTCZAK L. Fatty acids as modulators of the cellular production of reactive oxygen species [J]. *Free Radical Bio Med*, 2008, 45(3): 231-241.
- [35] SORDILLO L M. Nutritional strategies to optimize dairy cattle immunity [J]. *J Dairy Sci*, 2016, 99(6): 4967-4982.
- [36] LI F, SHAH A M, WANG Z, et al. Effects of land transport stress on variations in ruminal microbe diversity and immune functions in different breeds of cattle [J]. *Animals-Basel*, 2019, 9(9): 599
- [37] BAESSLER A, VIGNALI D A A. T Cell exhaustion [J]. *Annu Rev Immunol*, 2024, 42(1): 179-206.
- [38] QIAO K, JIANG R, CONTRERAS G A, et al. The Complex interplay of insulin resistance and metabolic inflammation in transition dairy cows [J]. *Animals-Basel*, 2024, 14(6): 832
- [39] QI J, HUANG F, GAN L, et al. Multi-omics investigation into long-distance road transportation effects on respiratory health and immunometabolic responses in calves [J]. *Microbiome*, 2024, 12(1): 242.
- [40] ZHANG Y, LI X, ZHANG H, et al. Non-esterified fatty acids over-activate the TLR2/4-NF-Kappab signaling pathway to increase inflammatory cytokine synthesis in neutrophils from ketotic cows [J]. *Cell Physiol Biochem*, 2018, 48(2): 827-837.
- [41] HULBERT L E, CARROLL J A, BURDICK N C, et al. Innate immune responses of temperamental and calm cattle after transportation [J]. *Vet Immunol Immunop*, 2011, 143(1): 66-74.
- [42] VELLS L, RØNTVED C M, BJERRING M, et al. Cytokine and acute phase protein gene expression in repeated liver biopsies of dairy cows with a lipopolysaccharide-induced mastitis [J]. *J Dairy Sci*, 2009, 92(3): 922-934.
- [43] BAGATH M, KRISHNAN G, DEVARAJ C, et al. The impact of heat stress on the immune system in dairy cattle: A review [J]. *Res Vet Sci*, 2019, 126: 94-102.
- [44] SIRISINHA S. Insight into the mechanisms regulating immune homeostasis in health and disease [J]. *Asian Pac J Allergy*, 2011, 29(1): 1-14.
- [45] MARQUES R S, COOKE R F, FRANCISCO C L, et al. Effects of twenty-four hour transport or twenty-four hour feed and water deprivation on physiologic and performance responses of feeder cattle [J]. *J Anim Sci*, 2012, 90(13): 5040-5046.
- [46] ZHANG X, MOSSER D M. Macrophage activation by endogenous danger signals [J]. *J Pathol*, 2008, 214(2): 161-178.
- [47] DIONISIO F, TOMAS L, SCHULZ C. Glycolytic side pathways regulating macrophage inflammatory phenotypes and functions [J]. *Am J Physiol Cell Physiol*, 2023, 324(2): C558-C564.
- [48] VIEIRA S M, LEMOS H P, GRESPAN R, et al. A crucial role for TNF-alpha in mediating neutrophil influx induced by endogenously generated or exogenous chemokines, KC/CXCL1 and LIX/CXCL5 [J]. *Brit J Pharmacol*, 2009, 158(3): 779-789.
- [49] GRIFFIN G K, NEWTON G, TARRIO M L, et al. IL-17 and TNF-alpha sustain neutrophil recruitment during inflammation through synergistic effects on endothelial activation [J]. *J Immunol*, 2012, 188(12): 6287-6299.
- [50] NAUSEEF W M. Assembly of the phagocyte NADPH oxidase [J]. *Histochem Cell Biol*, 2004, 122(4): 277-291.
- [51] VERMOT A, PETIT-HARTLEIN I, SMITH S, et al. NADPH oxidases (NOX): an overview from discovery, molecular mechanisms to physiology and pathology [J]. *Antioxidants-Basel*, 2021, 10(6): 890
- [52] ZHAO H, TANG X, WU M, et al. Transcriptome characterization of short distance transport stress in beef cattle blood [J]. *Front Genet*, 2021, 12: 616388.
- [53] ALHUSSIEN M N, DANG A K. Interaction between stress hormones and phagocytic cells and its effect on the health status of dairy cows: A review [J]. *Vet World*, 2020, 13(9): 1837-1848.
- [54] GALYEAN M L, LEE R W, HUBBERT M E. Influence of fasting and transit on ruminal and blood metabolites in beef steers [J]. *J Anim Sci*, 1981, 53

- (1):7-18.
- [55] TORAL P G, HERVAS G, FERNANDEZ-DIEZ C, et al. Rumen biohydrogenation and milk fatty acid profile in dairy ewes divergent for feed efficiency[J]. *J Dairy Sci*, 2021, 104(5):5569-5582.
- [56] DIJKSTRA J, ELLIS J L, KEBREAB E, et al. Ruminal pH regulation and nutritional consequences of low pH[J]. *Anim Feed Sci Tech*, 2012, 172(1-2):22-33.
- [57] KOGUT M H, LEE A, SANTIN E. Microbiome and pathogen interaction with the immune system [J]. *Poult Sci*, 2020, 99(4):1906-1913.
- [58] RENGARAJAN S, KNOOP K A, RENGARAJAN A, et al. A potential role for stress-induced microbial alterations in IgA-associated irritable bowel syndrome with diarrhea[J]. *Cell Rep Med*, 2020, 1(7):100124
- [59] SUZUKI K, MEEK B, DOI Y, et al. Aberrant expansion of segmented filamentous bacteria in IgA-deficient gut[J]. *Proc Natl Acad Sci U S A*, 2004, 101(7):1981-1986.
- [60] KAWAMOTO S, MARUYA M, KATO L M, et al. Foxp3(+) T cells regulate immunoglobulin a selection and facilitate diversification of bacterial species responsible for immune homeostasis [J]. *Immunity*, 2014, 41(1):152-165.
- [61] SHULZHENKO N, MORGUN A, HSIAO W, et al. Crosstalk between B lymphocytes, microbiota and the intestinal epithelium governs immunity versus metabolism in the gut[J]. *Nat Med*, 2011, 17(12):1585-1593.
- [62] THOETKIATTIKUL H, MHUANTONG W, LAOTHANACHAREON T, et al. Comparative analysis of microbial profiles in cow rumen fed with different dietary fiber by tagged 16S rRNA gene pyrosequencing [J]. *Curr Microbiol*, 2013, 67(2):130-137.
- [63] VINAYAMOHAN P G, POELSTRA J, CHENG T, et al. Exploring the effects of transport duration on the fecal microbial communities of surplus dairy calves[J]. *J Dairy Sci*, 2024, 107(6):3863-3884.
- [64] LI Y, MAO K, ZANG Y, et al. Revealing the developmental characterization of rumen microbiome and its host in newly received cattle during receiving period contributes to formulating precise nutritional strategies[J]. *Microbiome*, 2023, 11(1):238.

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