ISSN: 2378-3672

Shao LD, et al. Int J Immunol Immunother 2026, 13:077
DOI: 10.23937/2378-3672/1410077
Volume 13 | Issue 1
Open Access

International Journal of Immunology and Immunotherapy

REVIEW ARTICLE

Lac-Phe: An Exercise Induced Metabolite with Immunomodulatory Potential in Inflammatory Diseases

*Ling Duo Shao, Meng Qi Yang, Hong Yu Xu and Li Chen**

Department of Neurology, The First Affiliated Hospital of Guangxi Medical University, China

Corresponding author: *Li Chen, Department of Neurology, The First Affiliated Hospital of Guangxi Medical University, No. 6, Shuangyong Road, Nanning City, Nanning, 530021, China*

Abstract

Physical exercise confers systemic immunomodulatory benefits, yet the molecular mediators linking metabolic stress to immune cell reprogramming remain incompletely defined. N-lactoyl-phenylalanine (Lac-Phe), a lactate-phenylalanine conjugate synthesized by carnosine dipeptidase 2 (CNDP2), has emerged as a critical exercise-derived metabolite that bridges peripheral energy metabolism with central and peripheral immune regulation. This review systematically summarizes the biosynthetic regulatory network of Lac-Phe, with emphasis on its immunomodulatory functions. And translational advances include biomimetic scaffolds enabling localized Lac-Phe release for tissue regeneration and the first human clinical trial (NCT06743009) evaluating its metabolic and immunomodulatory efficacy. Nevertheless, the unidentified direct membrane receptor on immune cells, unaddressed safety risks of long-term immune modulation, and immature immune-targeted delivery approaches impede clinical translation. Future priorities should focus on receptor identification through chemical proteomics and CRISPR screening, determination of the pharmacological safety window for chronic immunomodulation, and development of localized delivery strategies to accelerate clinical application in immune-mediated disorders.

Keywords

N-Lactoyl-Phenylalanine, Exerkine, Immunometabolism, CNDP2

Abbreviations

CNDP2: Carnosine dipeptidase 2; **IBD:** Inflammatory bowel disease; **Lac-Phe:** N-lactoyl-phenylalanine; **MELAS:** Mitochondrial Encephalomyopathy, Lactic Acidosis, and Stroke-Like Episodes; **MGWAS:** Metabolome-Wide Genome-Wide Association Study; **SCI:** Spinal Cord Injury; **SGGT:** Solution-Gated Graphene Field-Effect Transistor; **SLC17A1/3:** Solute Carrier Family 17 Members 1 and 3

Introduction

Physical exercise is a potent immunomodulatory intervention that regulates immune cell trafficking, inflammatory cytokine profiles, and tissue-resident macrophage polarization across multiple organ systems [1,2]. Regular physical activity reduces systemic low-grade inflammation, a hallmark of metabolic diseases, autoimmune disorders, and accelerated immunosenescence [3]. However, the circulating molecular mediators that transduce metabolic signals from contracting skeletal muscle to distal immune compartments have only begun to be elucidated.

N-lactoyl-phenylalanine (Lac-Phe) is a representative functional exercise-derived metabolite discovered through advances in metabolomics [4]. In 2022, it was identified as a core appetite-suppressing metabolite induced by exercise, rapidly becoming a research focus in the metabolic field [5]. While initially characterized as an anorexigenic metabolite suppressing feeding behavior through hypothalamic AgRP neuron inhibition [6], emerging evidence positions Lac-Phe as a pleiotropic immunometabolic signal. Lac-Phe modulates macrophage/microglial polarization states, suppresses NF-κB-driven inflammation in intestinal mucosa, and promotes AMPK-PGC1α-mediated metabolic reprogramming in neuroimmune contexts [7,8]. These findings establish Lac-Phe as a molecular effector linking exercise-induced metabolic stress to innate immune cell plasticity.

Despite rapid progress, several fundamental questions constrain the immunological understanding

Citation: Shao LD, Yang MQ, Xu HY, et al. (2026) Lac-Phe: An Exercise Induced Metabolite with Immunomodulatory Potential in Inflammatory Diseases. Int J Immunol Immunother 12:076. doi.org/10.23937/2378-3672/1410076

Accepted: June 04, 2026 : **Accepted:** July 02, 2026 : **Published:** July 06, 2026

of Lac-Phe. First, the direct membrane receptor or immune cell-specific transducer of Lac-Phe remains unidentified [9]. Second, whether Lac-Phe functions as a hormone, a paracrine immunometabolic cue, or both, is unresolved. Third, the therapeutic window for Lac-Phe-mediated immunomodulation, particularly the threshold between physiological anti-inflammatory effects and potential immunosuppressive risks, has not been defined.

This review systematically integrates existing research progress centered on immunology, rather than mere metabolic regulation [10,11], to elaborate Lac-Phe's biosynthetic features, core immunomodulatory mechanisms, pathological roles in diverse inflammatory diseases, and latest translational achievements, alongside pending research bottlenecks requiring further exploration.

Biosynthesis and Cellular Sources: An Immunometabolic Perspective

Enzymatic basis and tissue-specific expression

CNDP2 serves as the rate-limiting catalytic enzyme responsible for endogenous Lac-Phe biosynthesis via the condensation of lactate and L-phenylalanine [5,12]. Beyond its well-documented expression in skeletal muscle, intestinal epithelium and adipose tissues, abundant CNDP2 expression has been validated in innate immune cells including tissue macrophages and central nervous system-resident microglia, which endows these immune populations with autonomous Lac-Phe synthetic capacity [5,13,14].

Lac-Phe pools originating from exercise versus pharmacological induction possess disparate tissue origins and divergent systemic immunological effects [15]. A single bout of high-intensity sprint interval training acutely elevates plasma Lac-Phe from a resting concentration of approximately 0.1 μM to nearly 0.2 μM within 30-60 minutes post-exercise [5]. Elevated Lac-Phe levels are positively correlated with exercise intensity: sprint exercise > resistance training > moderate-intensity endurance exercise [16]. Such intensity-dependent variation is presumably attributed to lactate serving as the rate-limiting substrate, since high-intensity exercise markedly enhances glycolytic flux and triggers massive lactate production [17]. Meanwhile, CNDP2 transcript abundance negatively correlates with slow-twitch skeletal muscle proportion [14] and Long-term endurance training also upregulates Lac-Phe levels in patients with type 1 diabetes [18], partially explaining variable Lac-Phe induction amplitude among individuals with divergent exercise responsiveness.

By contrast, metformin-triggered Lac-Phe biosynthesis primarily occurs within intestinal epithelial $CNDP2^{+}$ cells [13,19]. In addition, diet also affects the level of Lac-Phe [19,20]. Metabolome-wide genome-wide association study (mGWAS) analyses indicate that Lac-Phe levels are predominantly influenced by dynamic metabolic or inflammatory states rather than by fixed genetic factors, further supporting the notion that its syn-thesis is highly regulated by environmental and physiological conditions [13].

Notably, detectable levels of circulating Lac-Phe persist in CNDP2 knockout mice [12], suggesting the existence of alternative synthetic pathways, implying that whether Lac-Phe derived from other tissues possesses distinct metabolic fates and biological functions remains entirely unknown.

The potential of Lac-Phe as an immune metabolic signal

Li, et al. identified solute carrier family 17 members 1 and 3 (SLC17A1/3) as the primary transporters mediating renal excretion of Lac-Phe [12]. SLC17A1/3 is highly expressed in renal tubular epithelial cells, and its overexpression significantly enhances transmembrane transport of Lac-Phe. Genetic ablation of SLC17A1/3 markedly reduces urinary Lac-Phe excretion without affecting plasma Lac-Phe levels, suggesting the existence of additional Lac-Phe metabolic mechanisms that remain to be elucidated[8]. Moreover, whether renal clearance of Lac-Phe is modulated by exercise, diet, or disease states remains completely unknown. This knowledge gap severely hampers the standardized application of urinary Lac-Phe as a clinical biomarker. Furthermore, plasma Lac-Phe levels are markedly elevated under severe stress conditions such as septic shock and are associated with poor prognosis, suggesting that clearance pathways may be suppressed under pathological stress [21].

Molecular Mechanisms of Lac-Phe-Mediated Immunomodulation

Spinal cord injury

Spinal cord injury (SCI) triggers secondary injury processes involving microglial/macrophage activation, inflammatory responses, and lipid metabolic dysregulation [22,23]. Lac-Phe modulates lipid metabolism in microglia/macrophages via the AMPK-PGC1α-PPARγ pathway, reducing lipid accumulation, suppressing inflammatory responses, and promoting functional recovery following SCI [8]. Lac-Phe activates the classical energy sensor AMPK, which in turn initiates the PGC1α-PPARγ transcriptional axis, a pathway typically associated with mitochondrial biogenesis and fatty acid oxidation [24], suggesting that Lac-Phe may achieve immunophenotypic switching by remodeling cellular energy metabolism. This study expands the potential application of Lac-Phe in central nervous system disorders, indicating that it may exert neuroprotective functions.

Inflammatory bowel disease

Serum Lac-Phe levels are decreased and colonic CNDP2 expression is downregulated in patients with inflammatory bowel disease (IBD), suggesting that Lac-Phe deficiency may contribute to the pathological process [25]. Yu, et al. demonstrated that Lac-Phe inhibits macrophage polarization toward the pro-inflammatory M1 phenotype while promoting the expression of anti-inflammatory M2 phenotype markers, an effect mediated through suppression of the NF-κB signaling pathway. In a dextran sulfate sodium-induced mouse model of colitis, exogenous Lac-Phe administration significantly alleviated disease severity, reduced colonic mucosal inflammatory cell infiltration, protected epithelial barrier integrity, and lowered colonic tissue inflammation scores [7]. This immunomodulatory effect provides a novel molecular mechanism underlying the anti-inflammatory benefits of exercise. Unlike the findings in spinal cord injury, where Lac-Phe activates AMPK, Lac-Phe primarily inhibits NF-κB in IBD, suggesting that the tissue microenvironment dictates the preferential engagement of downstream signaling pathways by Lac-Phe.

Hypertension

Preliminary studies have shown that Lac-Phe administration alleviates the elevation of both systolic and diastolic blood pressure in angiotensin II-induced hypertensive mice [26]. However, this finding requires validation in independent large-scale populations, and it remains unclear whether the hypotensive mechanism operates independently of the metabolic and immune effects of Lac-Phe. Given its anti-inflammatory and metabolic regulatory actions, Lac-Phe may confer cardiovascular protection through mechanisms such as improving vascular endothelial function and reducing oxidative stress. Nevertheless, direct evidence is currently limited, and further animal studies and clinical investigations are warranted to substantiate the cardiovascular protective potential of Lac-Phe.

Others

Plasma Lac-Phe levels are significantly elevated in patients with mitochondrial encephalomyopathy, lactic acidosis, and stroke-like episodes (MELAS), and correlate with disease severity. Mechanistically, this elevation may be attributed to lactate accumulation resulting from mitochondrial respiratory chain dysfunction, which provides substrate for Lac-Phe synthesis [27]. Furthermore, studies have indicated a correlation between Lac-Phe levels and cognitive function [28], consistent with the well-established effect of exercise in improving cognitive performance, suggesting that Lac-Phe may mediate the beneficial effects of exercise on brain health [29]. However, given the cross-sectional design of this study, only an association rather than causality can be inferred [30]. Future longitudinal cohort studies or Mendelian randomization analyses are warranted to evaluate the value of Lac-Phe as a biomarker of cognitive decline.

Future Development

Clinical translation: From clinical trials to delivery strategies

In 2025, the first human clinical trial of Lac-Phe (NCT06743009) was officially initiated. This study employs a double-blind, randomized, crossover design and aims to evaluate the effects of intravenously administered Lac-Phe on appetite, energy metabolism, and glucose homeostasis in individuals with obesity [9]. This clinical trial will provide critical evidence regarding the pharmacodynamic profile and safety of Lac-Phe in humans, representing an important milestone in translating basic research on Lac-Phe toward clinical applications. However, the intravenous route bypasses the local tissue production of Lac-Phe (e.g., in skeletal muscle and intestine) that occurs during exercise, and may therefore not fully recapitulate the pharmacokinetics and paracrine effects under physiological conditions. Consequently, alternative administration strategies that more closely mimic the physiological pattern remain to be developed.

In the context of local delivery, Liu, et al. constructed a bilayer biomimetic scaffold that enables timed-release by loading an anti-senescence peptide in the upper layer and Lac-Phe in the lower layer, synergistically modulating the immune and metabolic microenvironment and ultimately achieving simultaneous osteochondral tissue repair in an animal model [31]. This finding suggests that local application of Lac-Phe holds unique potential in tissue engineering and regenerative medicine. For metabolic indications requiring systemic action (e.g., obesity and type 2 diabetes), intestinally restricted release systems or prodrugs targeting specific organs need to be designed to increase local effective concentrations while mitigating the potential risks associated with high systemic exposure.

It must be emphasized that Hedaya, et al. found in cell models that high concentrations of Lac-Phe interfere with insulin signaling and impair mitochondrial respiration [32], serving as a caution that the pharmacological safety window of Lac-Phe may be narrow. Future clinical trials must first establish this therapeutic window and systematically evaluate the metabolic toxicity of long-term high-dose exposure. To date, no studies have explored the use of prodrugs or intestinally targeted delivery to circumvent high systemic exposure; this should become an important direction for medicinal chemistry and formulation research.

Detection technologies and receptor identification

In the realm of detection technologies, Li, et al. successfully constructed a biosensor capable of detecting L-lactate and L-phenylalanine based on

solution-gated graphene field-effect transistor (SGGT) technology, providing a novel technical approach for rapidly assessing individual responses to exercise [33]. Furthermore, a liquid chromatography-tandem mass spectrometry method using dried blood spot samples enables quantitative measurement of Lac-Phe concentrations at multiple time points before, during, and after exercise [34]. These technologies offer convenient tools for individualized exercise effect assessment and dynamic Lac-Phe monitoring in clinical studies.

In contrast, the direct membrane receptor or molecular target of Lac-Phe remains unidentified, representing the most critical bottleneck currently constraining mechanistic research and drug development. Although existing studies have shown that Lac-Phe increases KATP channel current in a dose-dependent manner [6], no evidence has demonstrated direct binding of Lac-Phe to the subunits of this channel. Similarly, the metabolite genome-wide association study (mGWAS) by Elashi, et al. did not identify significant genetic loci associated with Lac-Phe levels [35], suggesting that Lac-Phe may exert its functions through metabotropic receptors or transporters, a feature that further complicates target identification.

Based on these considerations, we propose the following priority research directions: (1) unbiased chemical proteomics approaches (e.g., photoaffinity probes, drug affinity responsive target stability [DARTS] technology) to directly capture Lac-Phe-binding proteins [36,37]; (2) CRISPR genome-wide screening to identify essential genes mediating the cellular effects of Lac-Phe [38]; and (3) upon target identification, structural biology studies to provide a foundation for subsequent drug design [39]. Prior to achieving these goals, any drug development efforts targeting Lac-Phe mimetics or antagonists will face considerable uncertainty.

Conclusion

Within just three years since its initial identification in 2022 as an exercise-induced appetite-suppressing metabolite, Lac-Phe research has rapidly progressed from fundamental mechanistic exploration toward clinical translation. Lac-Phe modulates macrophage/microglial polarization in immunoregulation, demonstrating therapeutic potential in conditions such as SCI and IBD. Nevertheless, the unidentified direct membrane receptor, the unclear safety window, and the lack of local delivery strategies represent three core obstacles limiting its clinical translation. Future priorities should therefore focus on target identification, determination of the therapeutic window, and optimization of delivery strategies.

Acknowledgments

Not applicable.

Funding Sources

This study was supported by the Guangxi Medical and Health Appropriate Technology Development and Application Project (Grant/Award Number: 'S2021107'); Clinical Research "Climbing" Program of the First Affiliated Hospital of Guangxi Medical University (Grant/Award Number: 'YYZS2021002'); and National Natural Science Foundation of China (Grant/Award Number: '82260367', '82271371').

Disclosures

The content is solely the responsibility of the authors and the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Lingduo Shao: Conceived and designed research, drafted manuscript.

Mengqi Yang: Edited and revised manuscript.

Hongyu Xu: Edited and revised manuscript.

Li Chen: Edited and revised manuscript, approved final version of manuscript.

References

1. Fiuza Luces Carmen, Pedro Valenzuela L, Beatriz Gálvez G, Manuel Ramírez, Alejandro López-Soto, et al. (2024) The effect of physical exercise on anticancer immunity. Nat Rev Immunol 24: 282-293.
2. Peng Mengyuan, Niannian Li, Hongbo Wang, Yaxu Li, Hui Liu, et al. (2025) Macrophages: Subtypes, distribution, polarization, immunomodulatory functions, and therapeutics. MedComm 6: e70304.
3. Cifuentes Mariana, Hugo Verdejo E, Pablo Castro F, Alejandro Corvalan H, Catterina Ferreccio, et al. (2025) Low-grade chronic inflammation: A shared mechanism for chronic diseases. Physiology (Bethesda) 40.
4. Jansen Robert S, Ruben Addie, Remco Merkx, Alexander Fish, Sunny Mahakena, et al. (2015) N-lactoyl-amino acids are ubiquitous metabolites that originate from CNDP2-mediated reverse proteolysis of lactate and amino acids. Proc Natl Acad Sci USA 112: 6601-6006.
5. Li Veronica L, Yang He, Kévin Contrepois, Hailan Liu, Joon T Kim, et al. (2022b) An exercise-inducible metabolite that suppresses feeding and obesity. Nature 606: 785-790.
6. Liu Hailan, Veronica Li L, Qingzhuo Liu, Yao Liu , Cunjin Su, et al. (2025) Lac-Phe induces hypophagia by inhibiting AgRP neurons in mice. Nature Metabolism 7: 2004-2017.
7. Yu Runfeng, Chi Zhang, Ming Yuan, Shubiao Ye, Tuo Hu, et al. (2025) Exercise-induced metabolite N-Lactoyl-phenylalanine ameliorates colitis by inhibiting M1 macrophage polarization via the suppression of the NF-κB signaling pathway. Cell Mol Gastroenterol Hepatol 19: 101558.
8. Ying Weiyang, Weidong Weng, Peifang Wang, Chi Pan, Jiani Qiu, et al. (2025) N-Lactoyl-phenylalanine modulates lipid metabolism in microglia/macrophage via the AMPK-PGC1α-PPARγ pathway to promote recovery in mice with spinal cord injury. J Neuroinflammation 22: 167.

9. Oni Olaiya Peter, Barry Scott, Lily Schwartz C, Tyson MacCormack J, Mohammed Hankir, et al. (2026) Beyond exercise and appetite: The expanding biology and therapeutic potential of N-Lactoyl-phenylalanine. J Pharmacol Exp Ther 393: 103798.

10. Enko Dietmar, Andreas Meinitzer, Christine Dawczynski, Zelzer Sieglinde, Pilz Stefan, et al. (2025) The exercise-induced appetite suppressor N-Lactoyl-phenylalanine is linked with glucose metabolism. Clinical Laboratory 71: 609.

11. Yao Taikang, Guolin Alexander Wen, Zhenchao Wu, Ning Shen (2025) Lac-Phe: A central metabolic regulator and biomarker. Med Rev 5: 429-431.

12. Li Veronica L, Shuke Xiao, Pascal Schlosser, Nora Scherer, Amanda Wiggenhorn L, et al. (2024) SLC17A1/3 transporters mediate renal excretion of lac-phe in mice and humans. Nat Commun 15: 6895.

13. Xiao Shuke, Veronica Li L, Xuchao Lyu, Xudong Chen, Wei Wei, et al. (2024b) Lac-Phe mediates the effects of metformin on food intake and body weight. Nat Metab 6: 659-669.

14. Sellami Maha, Khaled Naja, Shamma Almuraikhy, Najeha Anwardeen, Rinat Sultanov I, et al. (2025) N-Lactoyl amino acids as metabolic biomarkers differentiating low and high exercise response. Biol Sport 42: 331-344.

15. TeSlaa Tara (2024) Metformin induces a lac-phe gut-brain signalling axis. Nat Metab 6: 603-605.

16. Weber Dirk, Paola Ferrario G, Achim Bub (2025) Exercise intensity determines circulating levels of Lac-Phe and other exerkines: A randomized crossover trial. Metabolomics 21: 63.

17. Xiao Shuke, Veronica Li L, Jonathan Long Z (2024) Lac-Phe (N-Lactoyl-Phenylalanine). Trends in Endocrinology and Metabolism: TEM 35: 758-759.

18. Glatz Ulrike, Alexander Müller, Othmar Moser, Felix Aberer, Tobias Niedrist, et al. (2026) Acute and prolonged effects of aerobic endurance training on N-lactoyl-phenylalanine and inflammatory markers in individuals with type 1 diabetes: An exploratory analysis of the ultraflexi-1 study. Diabetes Obes Metab 28: 771-774.

19. Scott Barry, Emily Day A, Katie O'Brien L, John Scanlan, Grace Cromwell, et al. (2024) Metformin and feeding increase levels of the appetite-suppressing metabolite lac-phe in humans. Nat Metab 6: 651-658.

20. Berkel Caglar, Ercan Cacan (2023) Trans-10, Cis-12 conjugated linoleic acid- and caloric restriction-mediated upregulation of CNDP2 expression in white adipose tissue in rodents, with implications in feeding and obesity. The J Nutr Biochem 114: 109269.

21. Rogers Robert S, Rohit Sharma, Hardik Shah B, Owen Skinner S, Xiaoyan Guo A, et al. (2024) Circulating N-Lactoyl-amino acids and N-Formyl-methionine reflect mitochondrial dysfunction and predict mortality in septic shock. Metabolomics 20: 36.

22. Fu Sheng-Ping, Si-Yu Chen, Qi-Ming Pang, Meng Zhang, Xiang-Chong Wu, et al. (2022) Advances in the research of the role of macrophage/microglia polarization-mediated inflammatory response in spinal cord injury. Front Immunol 13: 1014013.

23. Hu, Yue, Jun Gao (2025) The role of polarization dynamics in macrophages and microglia on the inflammatory microenvironment of spinal cord injury. Mol Cell Neurosci 135: 104054.

24. Yang Minmin, Bowen Hu, Donglei Sun, Changbin Zhao, Haohui Wei, et al. (2022) Growth hormone receptor gene influences mitochondrial function and chicken lipid metabolism by AMPK-PGC1α-PPAR signaling pathway. BMC Genomics 23: 219.

25. Schumacher Michael A (2026) From muscle to macrophage: An anti-inflammatory role for the metabolite N-Lactoyl-phenylalanine in inflammatory bowel disease. Cell Mol Gastroenterol Hepatol 20: 101643.

26. Tan Xin, Xianyun Jiang, Lu Ren, Ziyu Meng, Jingyi Yang, et al. (2026) Determination of N-Lactoyl-phenylalanine, phenylacetylglutamine and trimethylamine-N-Oxide related metabolites in hypertensive patients by liquid chromatography-mass spectrometry and the application to blood pressure regulation. Journal of Pharmaceutical and Biomedical Analysis 271: 117327.

27. Sharma Rohit, Bryn Reinstadler, Kristin Engelstad, Owen Skinner S, Erin Stackowitz, et al. (2021) Circulating markers of NADH-reductive stress correlate with mitochondrial disease severity. J Clin Invest 131: 136055.

28. Jost Zbigniew, Maciej Chroboczek, Marta Skurewicz-Palicka, Angelika Sawicka, Milena Deptuła, et al. (2026) N-Lactoyl-phenylalanine as a Possible biomarker of cognition? association between neuroproteins, cytokines, body composition, physical fitness and cognitive function in older adults. Geroscience.

29. Xu Liya, Hongyi Gu, Xiaowan Cai, Yimin Zhang, Xiao Hou, et al. (2023) The effects of exercise for cognitive function in older adults: A systematic review and meta-analysis of randomized controlled trials. Int J Environ Res Public Health 20: 1088.

30. Savitz David A, Gregory Wellenius A (2023) Can cross-sectional studies contribute to causal inference? It Depends. Am J Epidemiol 192: 514-516.

31. Liu Po-Lin, Shu-Hang He, Zhi-Han Shen, Xu-Ran Li, Qing-Song Deng, et al. (2025) Bilayer scaffolds synergize immunomodulation and rejuvenation via layer-specific release of CK2.1 and the 'exercise hormone' Lac-Phe for enhanced osteochondral regeneration. Adv Healthc Mater 14: e2402329.

32. Hedaya Laila, Khaled Naja, Shamma Almuraikhy, Najeha Anwardeen, Asma A Elashi, et al. (2025) N-Lactoyl phenylalanine disrupts insulin signaling, induces inflammation, and impairs mitochondrial respiration in cell models. Cells 14: 1296.

33. Li Jiacheng, Ming Zhang, Cailing Zhang, et al. (2025) Rapid indirect detection of N-Lactoyl-phenylalanine using dual DNA biosensors based on solution-gated graphene field-effect transistor. Biosens Bioelectron 273: 117149.

34. Bauhaus H, Möller T, Keller S, Thomas A, Braun H, et al. (2025) Proof-of-concept of a prior validated LC-MS/MS method for detection of N-Lactoyl-phenylalanine in dried blood spots before, during and after a performance diagnostic test of junior squad triathletes. Front Sports Act Living 7: 1600714.

35. Elashi Asma A, Aleem Razzaq, Najeha Anwardeen, et al. (2025) N-Lactoyl amino acids: Insights from metabolite genome-wide association studies and phenome-wide association analysis. Hum Mol Genet 34: 1865-1873.

36. Kozoriz Kostiantyn, Jun-Seok Lee (2025) Chemical proteomics for a comprehensive understanding of functional activity and the interactome. Chem Soc Rev 54: 6186-6207.

37. Dong ZC, Wang Y, Yang F, Wan F (2022) A brief introduction to chemical proteomics for target deconvolution. Eur Rev Med Pharmacol Sci 26: 6014-6026.

38. Chen Haojie, Keqin Dong, Jie Ding, et al. (2024) CRISPR genome-wide screening identifies PAK1 as a critical driver of ARSI cross-resistance in prostate cancer progression. Cancer Lett 587: 216725.

39. Staszak Maciej, Katarzyna Staszak, Karolina Wieszczycka, Anna Bajek, Krzysztof Roszkowski, et al. (2022) Machine learning in drug design: Use of artificial intelligence to explore the chemical structure-biological activity relationship. WIREs Computational Molecular Science 12: e1568.