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β-alanine: A Comprehensive Review of Athletic and Systemic Benefits

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ABSTRACT

Purpose: This paper aims to critically review the latest research on β-alanine supplementation, examining its impact on muscle performance, endurance, and overall athletic output. In addition, the study explores the supplement's systemic effects – including metabolic regulation and cognitive function—while addressing optimal dosing strategies and potential health risks.

Methodology: A comprehensive literature review was conducted using multiple scientific databases, including PubMed, Scopus, and Google Scholar. The selection criteria prioritized clinical trials, systematic reviews, and meta-analyses that investigated the effects of β-alanine on muscular function, metabolic parameters, and cognitive outcomes. Studies were evaluated for their methodological rigor, relevance, and practical applications, with special attention given to the mechanisms underlying β-alanine's role in increasing muscle carnosine levels and mitigating exercise-induced fatigue.

Findings: The review found that β-alanine supplementation effectively elevates muscle carnosine levels, enhancing the muscle's buffering capacity against acid accumulation during

high-intensity exercise. This biochemical improvement is associated with delayed onset of fatigue and enhanced performance in short-duration, high-intensity activities. Additionally, emerging evidence suggests that β-alanine may offer ancillary benefits, such as improved glucose regulation, reduced oxidative stress, and potential cognitive enhancements under stressful conditions.

Conclusions: β-alanine supplementation represents a promising ergogenic aid for athletes, with multifaceted benefits that extend beyond muscle performance to include metabolic and cognitive health. Current research supports its efficacy in improving anaerobic performance and delaying fatigue. These insights can guide athletes, trainers, and healthcare professionals in the strategic integration of β-alanine into performance and recovery regimens.

1. Introduction

Proper nutrition and supplementation are fundamental to optimizing athletic performance, aiding recovery, and enhancing the body's ability to adapt to physical training. Both amateur and professional athletes presently rely on various supplementation strategies to maximize their training outcomes, including synthetic ergogenic agents and natural performance-enhancing substances. Among these, amino acid-based supplements play a particularly significant role in supporting endurance, strength, and muscular recovery.

Amino acids are the building blocks of proteins, and thus contribute to muscle repair and growth while also influencing fatigue resistance and energy metabolism. Specific amino acids such as β-alanine, branched-chain amino acids (BCAAs), and essential amino acids (EAAs) are widely used to improve athletic performance. β-alanine, for instance, is known for its ability to increase muscle carnosine levels, which helps buffer acid accumulation in muscles during intense exercise, thereby delaying fatigue and improving high-intensity exercise performance. This makes it particularly beneficial for athletes engaged in sprinting, weightlifting, and other activities requiring short bursts of power.

This article endeavors to review the latest research on β-alanine, emphasizing its effects on not only muscular but also systemic functions, as well as the establishment of optimal supplementation dosages and potential health risks. Furthermore, this review will explore the

impact of β-alanine on other organs of the body to deliver a comprehensive analysis of its supplementation.

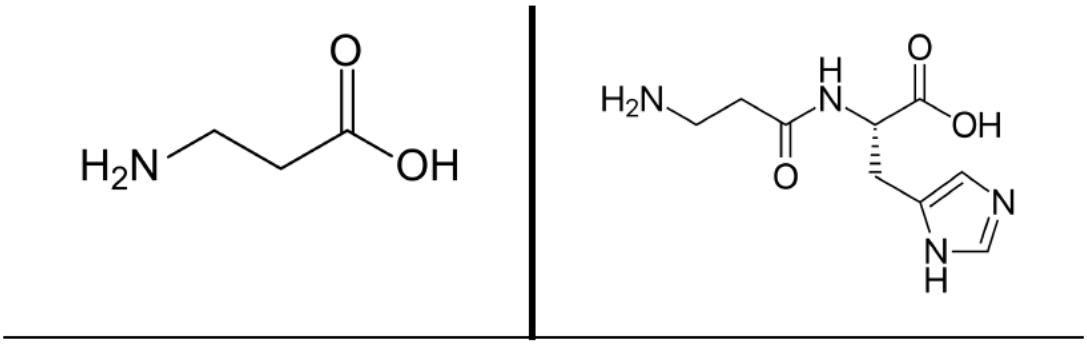
2. Methodology

The research utilized a comprehensive review of existing literature, sourcing studies from databases including PubMed, Scopus, and Google Scholar. The selection criteria focused on clinical trials, systematic reviews, and meta-analyses that explored the effects of β-alanine supplementation on muscle function, endurance, and overall athletic performance. In addition to muscular effects, the review also considered the impact of these amino acids on other physiological systems, such as cardiovascular and metabolic function, recovery, and fatigue resistance. The findings were then evaluated for their relevance and potential practical applications in improving sports performance, recovery, and overall health.

3. The Mechanism of Action

β-alanine

β-alanine (3-aminopropanoic acid) is a non-essential amino acid that acts as the rate-limiting precursor for carnosine synthesis. Through the action of carnosine synthetase, β-alanine combines with L-histidine to form carnosine, a dipeptide that functions as an intracellular proton buffer, which is mainly stored in muscular tissue that is devoid of carnosinase, the enzyme that breaks down carnosine. In contrast, serum carnosinase in humans rapidly degrades ingested carnosine, limiting its efficacy as a direct nutritional supplement (1).



β-alanine structure Carnosine structure

Carnosine's pKa of 6.83 causes it to be more efficient at sequestering protons than bicarbonate (pKa 6.3) or inorganic phosphate (pKa 7.2) across the physiological pH range (2). The presence of the imidazole ring on carnosine allows it to accept protons at normal pH, suggesting that the

molecule's buffering capability may occur before the bicarbonate system is engaged during anaerobic exercise, delaying the onset of muscle fatigue (3).

Emerging research indicates that β-alanine supplementation not only supports anaerobic performance through improved acid-base homeostasis but also promotes oxidative metabolism by upregulating transcription factors such as peroxisome proliferator-activated receptor β/δ (PPARβ/δ) and mitochondrial transcription factor A (TFAM), which in turn stimulate mitochondrial biogenesis and elevate oxygen consumption. In addition, β-alanine has been linked to the induction of myocyte enhancer factor 2 (MEF-2), leading to increased expression of glucose transporter 4 (GLUT4) and potentially enhancing glucose uptake in skeletal muscle, thereby supporting both anaerobic and aerobic energy production pathways (4).

Beyond its buffering capacity, carnosine acts as an antioxidant by neutralizing free radicals and singlet oxygen. When conjugated with L-histidine to form carnosine, it contributes to neuroprotection in the brain through multifaceted antioxidant mechanisms. The β-alanine moiety within carnosine enhances its ability to scavenge reactive oxygen species. This activity is largely mediated by the imidazole ring of the histidine residue, which donates hydrogen atoms to neutralize peroxyl radicals and mitigate oxidative damage to lipids, proteins, and nucleic acids in neuronal membranes. In addition to its radical-scavenging properties, carnosine also exhibits metal-chelating capabilities, particularly for transition metals such as copper. By binding these metals, carnosine limits their participation in Fenton-like reactions that generate deleterious free radicals. Together, these mechanisms shield the brain's high lipid content from oxidative stress (5, 6).

As such, increasing carnosine through β-alanine supplementation may not only improve exercise performance and training quality, but also help stave off oxidative stress in different parts of the body, such as the central nervous system. Studies examining those auxiliary effects are still in the early stages, however, and further research is required to fully determine β-alanine's effects on non-muscular systems.

4. β-alanine impact on muscular function

The supplementation of β-alanine has been repeatedly shown to enhance performance, improve muscle function and decrease fatigue during exercise (8). A systematic review examining its effect on sports performance has demonstrated that continued supplementation (4-6g per day), through its role in increasing muscle carnosine concentration, decreased neuromuscular fatigue, especially in older individuals (9). Statistically significant ($p < 0.05$) improvements have been demonstrated in studies examining exercises ranging from one to four minutes, however, no

improvement was shown for exercises below that time threshold, and negligible improvement was shown for exercises lasting for more than four minutes (10). Therefore, one can expect β-alanine supplementation to be most effective in improving performance in high-intensity activities or short-duration sports.

A study examining β-alanine's effects in various sports corroborated those findings, by demonstrating that for high-intensity exercises such as climbing, rowing or combat sports, β-alanine monotherapy had a positive effect on muscular capacity, although, it also posited that it did not have an effect on improving muscular strength unlike creatine – another popular supplement (11, 12, 13). Those findings were inconsistent with another study, in which a significant ($p < 0.05$) improvement in cumulative force punch force in boxers was observed.

Another study scrutinizing the performance of elite judo athletes between the ages of 19 – 23 showed a significant increase in Lower and Upper Limb Total Work and Upper Limb Mean Power measured during Wingate Test when supplementing β-alanine at doses ranging from 4 g – 6 g per day. The Wingate test is a short, high-intensity cycling test used to assess anaerobic power and capacity, requiring participants to pedal as fast as possible against a predetermined resistance for 30 seconds. Variations exist where the test is performed using an arm crank ergometer instead of a cycle, allowing for the assessment of upper-body anaerobic power. Before and after β-alanine supplementation, athletes performed two 30-s Wingate tests for upper and lower limbs. β-alanine improved Lower and Upper Limb Total Work ($p < 0.001$) and Upper Limb Mean Power ($p < 0.001$), but did not improve Lower Limb Mean Power. No significant changes were found in the placebo group (15).

β-alanine supplementation has also been shown to improve vertical jump distance. A moderate effect for both lower body peak power ($d=0.72$; 95% CI, 0.09–1.35) and upper body power drop ($d=-0.91$; 95% CI, −1.61 to −0.17) were observed in one study (16), indicating improvements in the group supplementing β-alanine over a 10 week period. Those strength related findings might come as a surprise, considering that muscular strength is not limited by acidosis, which carnosine and by extension β-alanine primarily affect.

Other studies discussing β-alanine's effect on power showed no statistically significant differences (10, 17, 18), showing a need for further investigation on its effects on muscular power.

5. β-alanine impact on non-muscular systems

β-alanine has been widely studied for its role in muscle performance, but emerging research has suggested that it may also have implications for metabolic health. Some studies indicate

that β-alanine supplementation, through its role in increasing carnosine levels, could influence factors related to obesity, though results remain mixed. A recent meta-analysis has shown that supplementation with β-alanine can reduce fasting glucose and hemoglobin A1c (HbA1c) levels in both humans and rodents, suggesting a potential metabolic benefit (19). Additionally, carnosine has been observed to decrease reactive carbonyl species (RCS)-modified proteins and improve insulin-stimulated glucose uptake in skeletal muscle cells under glucolipotoxic conditions (20). This highlights a possible role for β-alanine in obesity-related conditions such as type 2 diabetes and cardiovascular disease.

Moreover, β-alanine supplementation has been associated with reductions in fasting insulin levels, although the degree of this effect varies across studies. Some research also suggests minor reductions in total cholesterol and fasting triglycerides, though these findings are inconsistent and require further validation. Despite these potential benefits, a systematic review of randomized controlled trials (RCTs) found that β-alanine supplementation did not significantly impact overall body weight, fat mass, fat-free mass, or fat percentage in adults. Additionally, factors such as dosage, duration of supplementation, sex, and age did not appear to influence these outcomes (20).

β-alanine impact on cognitive function

β-alanine supplementation has also gained attention for its potential effects on cognitive function. Carnosine, for which biosynthesis it is a substrate for, is present in the central nervous system (CNS), specifically in glial cells and certain neurons wherein it exhibits antioxidant and intracellular buffering function.

While research on this topic remains in its early stages, evidence suggests that β-alanine's main derivative, carnosine, through its function in maintaining cellular homeostasis and mitigating the harmful effects of reactive oxygen and nitrogen species, could theoretically support cognitive resilience under stress (21).

Studies examining the direct impact of β-alanine on cognitive function have produced mixed results. While some research found no statistically significant effects on cognitive performance (23), others indicated potential benefits, particularly in high-stress scenarios or when combined with physical exercise. For instance, a study using 6g/day of β-alanine supplementation over 30 days showed improved results in the Serial Sevens Test, in which participants were asked to repeatedly subtract 7 from 100, assessing their concentration, mental processing speed, and cognitive function. Results suggested enhanced cognitive processing speed and accuracy. However, a similar study by the same research team failed to replicate these findings,

highlighting the need for further investigation (23). A study investigated the effects of 10 weeks of β-alanine supplementation on cognitive function in 100 participants, who completed assessments such as the Montreal Cognitive Assessment (MoCA) and the Stroop pattern recognition test during each testing session. The MoCA is a 30-point screening tool designed to detect mild cognitive impairment by evaluating various cognitive domains, including attention, memory, language, and executive functions. The Stroop test measures cognitive flexibility and processing speed by assessing the interference between reading a color word and naming the ink color in which it is printed, highlighting the conflict between automatic and controlled cognitive processes. No significant differences between groups were observed in MoCA scores ($p = 0.19$). However, among participants with baseline MoCA scores at or below normal (≤ 26), those receiving β-alanine showed significant improvements in MoCA scores at mid-intervention (13.6%, $p = 0.009$) and post-intervention (11.8%, $p = 0.016$) compared to the placebo group. These findings suggest that β-alanine supplementation may enhance cognitive function in older adults with baseline cognitive impairment and potentially reduce depression scores (24).

One possible explanation for these inconsistent results is that β-alanine's cognitive benefits may only emerge under conditions that induce physical or mental fatigue. Research suggests that during military operations or intense physical exertion, β-alanine supplementation may help individuals maintain decision-making abilities and reduce errors in executive function. In contrast, studies conducted at rest have generally not observed any significant cognitive improvements (25).

The exact mechanism by which β-alanine might influence cognitive function remains unclear. One hypothesis is that increased brain carnosine levels contribute to neuroprotection and anxiety reduction, though human studies have not confirmed this effect. Another theory links carnosine to brain-derived neurotrophic factor (BDNF), a key molecule in brain health and cognitive function. While animal studies suggest that carnosine may enhance BDNF secretion, human studies have not found conclusive evidence of increased BDNF levels following β-alanine supplementation (26).

Despite the inconclusive findings, β-alanine supplementation remains an area of interest for athletes, military personnel, and individuals seeking cognitive resilience under stress. More research, particularly involving real-world high-stress environments, is necessary to determine whether β-alanine can reliably enhance cognitive performance. Until then, while the

supplement shows promise, it should be used with realistic expectations and in conjunction with other proven cognitive-enhancing strategies, such as proper nutrition, sleep, and exercise.

6. β-Alanine Supplementation and Dosage

β-alanine supplementation has been widely studied for its ability to enhance muscle carnosine levels, which play a key role in buffering acid during high-intensity exercise. While small doses of carnosine (0.5–2 g/day) have shown modest increases in muscle carnosine content, higher doses of β-alanine (3.2–6.4 g/day) over several weeks appear to yield more significant improvements in muscle performance (27). Studies suggest that supplementation within this range for 4 to 12 weeks can lead to increases in muscle carnosine content by 40–100%, which translates into enhanced muscle endurance and strength output (28).

For optimal results, β-alanine is often supplemented in divided doses throughout the day to mitigate the common side effect of paresthesia, a tingling sensation that occurs at higher doses (29). Sustained-release formulations have also been developed to improve bioavailability while reducing discomfort, making them a preferred option for many individuals (30). Research indicates that a high adherence rate is observed with sustained-release β-alanine, with minimal reported adverse effects even over extended periods (31).

Athletes looking to maximize their training benefits are advised to start with a daily dose of 3.2 g for at least eight weeks or a higher intake of 6.4 g for four weeks, followed by a maintenance dose of 1.2 g/day to sustain elevated carnosine levels. Studies have also highlighted that combining β-alanine with sodium bicarbonate may further enhance its ergogenic effects, particularly for activities lasting between 30 seconds and 10 minutes.

Importantly, long-term supplementation appears to be safe, with doses as high as 6.4 g/day for 24 weeks showing no adverse effects in healthy individuals. Short-term studies have even tested doses up to 12 g/day without reporting significant side effects, though further research is needed to establish an upper safety limit. While β-alanine supplementation is highly effective, individual responses may vary, and factors such as sex, body composition, and training regimen should be considered when determining an optimal dosage strategy (27).

7. Potential limitations of β-alanine supplementation

β-alanine supplementation is generally considered safe for healthy individuals when taken at the recommended doses. The most common side effect is paresthesia – a temporary tingling sensation that usually affects the face, neck, and back of the hands. This sensation tends to appear within 20 to 30 minutes after ingestion and typically subsides within an hour, with its

intensity depending on the dose. To reduce this effect, it is recommended to split the daily dosage into smaller portions or use sustained-release formulations (32).

In some cases, especially when dosage exceeds 800 mg, individuals may experience skin flushing in the face and neck. Additionally, gastrointestinal discomfort (including stomach cramps, nausea, and bloating) has been reported, particularly when the supplement is taken on an empty stomach or in large quantities. Taking β-alanine with food and dividing the total daily intake into several smaller doses can help alleviate these issues. Moreover, because β-alanine and taurine share similar transport mechanisms in the body, high doses of β-alanine might lower taurine levels, potentially affecting processes such as water balance and bile salt formation (30). A systematic risk assessment and meta-analysis have indicated that β-alanine supplementation may cause a slight increase in circulating alanine aminotransferase (ALT) levels. However, these increases generally remain within normal clinical ranges, suggesting that liver function is not adversely affected. No significant changes have been noted in other health biomarkers, and dropout rates in studies comparing β-alanine with a placebo were similar, underscoring its overall tolerability. In a feasibility study with adults who were overweight or obese, sustained-release β-alanine supplementation (4.8 g/day for three months) was well tolerated. Adherence exceeded 90%, side effects remained at or below baseline levels, and there was little evidence of negative impacts on cardiometabolic, cardiovascular, or clinical biochemical outcomes (32). In summary, when used as directed, β-alanine supplementation appears safe for healthy individuals. To minimize potential side effects, it is advisable to split the daily dose into smaller servings, use sustained-release forms, and consult a healthcare professional before starting supplementation – especially for individuals with pre-existing conditions or those taking other medications.

Conclusions

β-alanine supplementation stands out as a promising strategy to enhance athletic performance and muscle endurance. The comprehensive review of current literature highlights that elevating muscle carnosine levels plays a crucial role in buffering acid accumulation during high-intensity exercise, thereby delaying fatigue and improving performance. This mechanism is central to understanding how β-alanine supports short-duration, high-intensity activities and can be a valuable addition to an athlete's regimen.

Moreover, beyond its impact on muscular function, β-alanine appears to offer secondary benefits in areas such as metabolic regulation and cognitive resilience. The antioxidant properties of carnosine may contribute to reducing oxidative stress, while preliminary findings

suggest a potential role in stabilizing glucose metabolism and improving insulin sensitivity. These multifaceted benefits warrant further investigation, especially in populations at risk for metabolic disorders.

While the current evidence is encouraging, it also underscores the need for standardized dosing protocols and long-term safety studies. Future research should aim to refine supplementation strategies, explore synergistic effects with other ergogenic aids, and determine the optimal conditions under which β-alanine exerts its full benefits. Overall, β-alanine presents a viable option for athletes seeking both performance enhancement and broader health benefits.

Disclosure:

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