Adenosine in exercise adaptation

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By influencing the regulation of the mechanisms of angiogenesis, erythropoietin production, blood flow, myocardial glucose uptake, glycolysis, systolic blood pressure, respiration, plasma norepinephrine and epinephrine levels, adenosine may exert a significant effect on the body's adaptation response to exercise. However, adenosine's possible influence over the vasodilatory response to exercise in skeletal muscle is controversial and more research is required to resolve this issue. Various popular exercise training methods, such as cyclic training, interval training, and the 'warm down' from training may increase adenosine levels and thereby might enhance the response of adenosine-influenced adaptive mechanisms. Among the several classes of drugs which may enhance extracellular adenosine levels and thereby might augment adenosine-influenced adaptive mechanisms, are the anabolic and anti-inflammatory drugs (NSAIDs).

Keywords: Anabolic steroids, angiogenesis, erythropoiesis, non-steroidal anti-inflammatory drugs

Adenosine formation and metabolism

Adenosine, a purine, is a metabolic product of ATP with a half-life in human blood of about 10 s. It is reformed into adenosine triphosphate (ATP) and excess amounts are enzymatically converted via the purine catabolic pathway sequence, to inosine, hypoxanthine, xanthine and finally uric acid (Figure 1). Many cell types produce adenosine, including heart, skeletal muscle and brain. Adenosine can be derived from AMP and ultimately ATP (Figure 1) and because it has a short half-life, its release parallels metabolic activity in many cell types including heart and skeletal muscle. These characteristics make this purine an ideal barometer of the local activity of exercising muscle tissue. A high rate of ATP breakdown, such as occurs during exercise, results in high levels of adenosine. This adenosine can overwhelm the purine catabolic pathway (Figure 1) in the cell and the excess moves out, accumulating in the extracellular space and blood. Adenosine's enzymatic breakdown continues in the blood, its brief half-life resulting in a localization of higher adenosine concentrations in the areas experiencing the most adenosine synthesis. Lowering the rate of ATP use results in a net re-uptake of adenosine by the cells and subsequent enzymatic breakdown or reformation into ATP. High blood and extracellular levels of adenosine give this purine access to the body's extracellular regulatory receptors, through which adenosine may exert various regulative effects on the body's complex adaptation response to exercise.

Immediate responses to exercise

In many tissues, including skeletal muscle, heart and brain, adenosine is a potent vasodilator. It dilates blood vessels in response to anoxia (low oxygen concentration) and possibly in response to hypercapnia (high blood carbon dioxide concentration). This dilatory response takes place during even short bouts of hypoxia or hypercapnia (< 1 min) and is part of the body's initial response to metabolic stress. Since the half-life of adenosine is relatively short, those tissues that produce adenosine would be the primary target of benefits which may be derived from enhanced adenosine levels. This allows the body to make an appropriate, localized and graded, adaptive response to exercise stress. The effects of adenosine on skeletal muscle vasodilatation are found to be dose-dependent and ischaemic exercise increases the plasma concentration of adenosine. Furthermore, ischaemic contraction of skeletal muscle increases the venous concentration of adenosine within the

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**Figure 1.** A summary of the breakdown of ATP and the formation of adenosine with its subsequent reformation into ATP or enzymatic breakdown via the purine catabolic pathway (ATP, adenosine triphosphate; ADP, adenosine diphosphate; AMP, adenosine monophosphate).
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Other investigators have demonstrated that adenosine also increases heart rate, systolic blood pressure, plasma norepinephrine and epinephrine and it is hypothesized to be a part of the activation of the sympathoadrenal response.

Long-term responses to exercise

After exercise metabolic rate falls but for some time remains higher than in the basal condition. Since in skeletal and heart muscle tissue extracellular adenosine levels parallel metabolic activity, adenosine levels also fall, but for some time remain higher than in the pre-exercise state. These elevated postexercise adenosine levels may continue to exert an influence on the body's adaptation to exercise.

One of these adaptations may be angiogenesis (new blood vessel formation). Adenosine enhances new blood vessel growth in both normal and hypoxic conditions. Adenosine-induced angiogenic growth in these studies was abolished by agents which antagonize the action of adenosine. Further evidence of adenosine's regulatory action in angiogenesis was demonstrated with dipyridamole, an adenosine re-uptake inhibitor. Chronic administration of dipyridamole results in angiogenic growth in both the heart and skeletal muscle.

Another action of adenosine may be in the regulation of the production of the hormone erythropoietin. Erythropoietin is produced in the kidney and stimulates erythropoiesis (red blood cell production) in the bone marrow. Increased adenosine levels enhance erythropoietin production in mice and reduces erythropoietin production in normal individuals as well as in patients with erythrocytosis (excess red blood cell production) after renal transplant.

Exercise adaptive mechanisms

The role of adenosine in influencing the above adaptive mechanisms has some important implications in the field of exercise training.

First, athletes in training may receive the greatest erythropoietic and angiogenic adaptive benefits by creating high systemic levels of adenosine. Since adenosine production is dependent on the energy stress level and the rate of use of ATP, it follows that stressful training with high levels of ATP use per unit of time would increase adenosine levels and thereby enhance adenosine-influenced adaptive responses. This may be, in part, an explanation for the necessity of interval training. All athletes, even those whose sport requires an effort for a period of hours (i.e. marathon runners, triathletes, marathon cross-country skiers and road-race cyclists), require interval training to achieve peak performance. The higher levels of adenosine produced as a result of the increased rate of ATP utilization per unit of time during interval training may promote adenosine-influenced adaptive responses necessary for the enhancement of performance.
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Second, exercise adaptation through adenosine-influenced regulatory mechanisms may also explain the success of cyclic training. Cyclic training is the practice of following a high-stress training period with one or more low-stress training periods. Adenosine's influence is dependent on a high rate of ATP use. Glycogen is the chief carbohydrate storage molecule in animals. Glycogen is converted to glucose via glycogenolysis (glycogen breakdown) with the resulting glucose being converted to ATP via aerobic glycolysis (glucose breakdown) and the citric acid (Krebs) cycle (manufactures ATP). Although the levels of intramuscular ATP are never fully depleted, presumably as a cellular protective mechanism, glycogen stores are much more variable. Several consecutive days of high-stress training bouts can deplete skeletal muscle glycogen reserves46 and blood glucose levels51 thereby limiting the rephosphorylation of ATP (ADP + P → ATP; Figure 1) which reduces the rate of ATP resynthesis and potentially results in an ultimate decline in both ATP and adenosine levels. Indeed, in a recent study, 3 days of consecutive running or cycling at 75% of VO2max resulted in a reduction of skeletal muscle glycogen stores, blood glucose and uric acid synthesis (an adenosine metabolite; Figure 1) in human subjects47. This can result in the exhaustion stage of the general adaptation syndrome, described by Selye as a stage where further resistance to stress becomes impossible48, and results in a failure to adapt. Following a high-stress training session with one or more low-stress training sessions gives the body an opportunity to replenish the glycogen stores from which adenosine can ultimately be derived.

Third, the above evidence also supports the practice of exercise 'warm down'. Exercise 'warm down' is the practice of continuing to exercise for a short time at a low level of stress immediately following a high-stress bout of exercise. This reduced activity would presumably produce some adenosine adding to the high-stress postexercise adenosine levels and extending their recovery time to basal levels thereby promoting adenosine-influenced adaptive responses.

Finally, no discussion of chemistry and athletics would be complete without acknowledging the potential for abuse. Many chemical agents reduce the cellular re-uptake of adenosine in animals49 and they probably act in the same manner in humans. Inhibition of the cellular re-uptake of adenosine is effective in increasing adenosine levels as demonstrated by dipyridamole, an adenosine re-uptake inhibitor, which increases adenosine levels when administered orally to human subjects11. Drugs which reduce the cellular re-uptake of adenosine include some of the drugs in each of the following categories: (1) anabolic and corticosteroids; (2) anti-convulsants; (3) antidepressants; (4) antihistamines; (5) coronary vasodilators; (6) non-steroidal anti-inflammatory drugs (NSAIDs); and (7) some antibiotics49. The two most likely categories to be involved in athlete abuse are anabolic steroids and NSAIDs.

Anabolic steroids are drugs which enhance athletic performance and are banned in international athletic contests. They have many actions, one of which is the reduction of adenosine cellular re-uptake by some of these agents49. With regard to adenosine's activation of mechanisms which promote endurance performance (i.e. angio genesis and erythropoiesis), it has been observed that androgenic hormone therapy increases erythropoiesis in humans50. It is also interesting to note that when rats were 'sprint trained' to deduce whether or not Ben Johnson received benefits from anabolic steroid use in his 1988 Olympic 100-m run, researchers from South Africa concluded that he may have received endurance but not speed benefits51. Whether or not he may have gained benefits in acceleration was not addressed by these observers and will require further investigation. Many authors have written about the abuse of steroids in athletics. Some of the more undesirable side-effects of steroid abuse are altered liver function52 and possible myocardial infarction53. A current approach to the steroid abuse problem is to educate abusers and younger potential abusers about the undesirable side-effects of the misuse of steroids and provide alternatives such as strength training and appropriate nutrition54.

In contrast to steroids, NSAIDs are not banned in international competition and many are available over the counter at a reasonable price. NSAIDs inhibit the enzyme cyclo-oxygenase, responsible for the production of prostaglandins (local hormones)55. This mechanism was first proposed by Vane in 1971 who, in 1982, received the Nobel Prize partially in recognition of this discovery. Since 1971, inhibition of prostaglandin synthesis has been found to be the common denominator in NSAID actions with their potency of inhibition in vitro paralleling their anti-inflammatory potency in vivo. NSAIDs are usually abused in connection with relief from the pain of injury, e.g. those marathon runners who use NSAIDs to relieve pain from overuse injuries enabling them to carry on training56. The potential exists for further abuse of NSAIDs by using them to enhance adenosine levels and thereby realize an improved response to the adenosine-influenced adaptive mechanisms involved in exercise. Although it has not been directly demonstrated that NSAIDs increase adenosine levels, it is likely that some do since several are adenosine re-uptake inhibitors49, and inhibition of cellular re-uptake is an effective means of increasing adenosine levels11.12. Furthermore, dipyriddamole acts as an analgesic57 as do NSAIDs. Dipyriddamole's analgesic effect is probably due to adenosine's ability to depress the firing of central neurones58. Finally, increasing blood flow is a primary action of adenosine59 and the NSAIDs indomethacin and meclofenamate have also been shown to increase blood flow following sustained, maximal isometric contractions in dog gracilis muscles56. Similarly, the NSAIDs indomethacin and ibuprofen enhance anoxia-induced hyperaemia (increase in blood flow) in rat brain, an action likely to be mediated by adenosine59. Athletes might now have the ability to obtain an agent (NSAIDs) which may enhance athletic performance, that is available over the counter, and easier to obtain than alcohol or tobacco. Furthermore, over-the-counter NSAIDs are commonly viewed by the
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