Endocannabinoids and exercise

A Dietrich, W F McDaniel

Exercise induces changes in mental status, particularly analgesia, sedation, anxiolysis, and a sense of wellbeing. The mechanisms underlying these changes remain unknown. Recent findings show that exercise increases serum concentrations of endocannabinoids, suggesting a possible explanation for a number of these changes. This article provides an overview of this emerging field.

A
n exercise induced altered state of consciousness has long been appreciated by endurance athletes. The effect has been well documented in the popular literature and subjected to scientific investigation. In the late 1960s, the psychological changes associated with prolonged physical activity were often described as a “second wind.” A more contemporary label often applied to these exercise induced changes is the “runner’s high.” The runner’s high has been described subjectively as pure happiness, elation, a feeling of unity with one’s self and/or nature, endless peacefulness, inner harmony, boundless energy, and a reduction in pain sensation. These subjective descriptions are similar to the claims of distorted perception, atypical thought patterns, diminished awareness of one’s surroundings, and intensified introspective understanding of one’s sense of identity and emotional status made by people who describe drug or trance states.

As is the case with all phenomena related to consciousness and its alterations, the runner’s high is a private experience, and the evidence for its existence rests predominantly on verbal report. Scientific inquiry into the phenomenon has been restricted even further because of its ephemeral nature. For example, the runner’s high is not experienced by all runners, and this experience does not occur consistently in runners who have experienced it previously. These observations have left laymen and scientists wondering why and under which conditions the runner’s high occurs, or whether or not it exists at all.

Before the discovery of the opioids, exercise scientists tried to account for the analgesic and euphoric mental states with alterations in the catecholamines adrenaline (epinephrine) and noradrenaline (norepinephrine). With the discovery and subsequent characterization of the opioid receptor network and endogenous opioid peptides, an entirely different mechanism of action evolved. Soon thereafter, exercise induced changes in psychological functions were often described as being a direct consequence of alterations in endogenous opioid release. However, there are a number of serious problems with the “endorphin hypothesis.”

Studies examining the exercise-endorphin connection produced equivocal results, and many of the studies were plagued by methodological confounds. For instance, β endorphin has almost the same amino acid sequence as other members of the pro-opiomelanocortin family such as the adrenocorticotropic hormone, making cross reactivity to the detecting antibody a serious confound. Also, adrenocorticotropic hormone is a stress hormone that is known to increase with exercise, compounding the problem. There are also major inconsistencies between the endorphin hypothesis and the physiological and biochemical responses to endurance exercise. For instance, β endorphins bind best to the μ opioid receptor, the endogenous opioid system that mediates the analgesic and euphoric properties of the opiates. However, minimal activation of the same endogenous opioid system is also responsible for the severe respiratory depression, pinpoint pupils, and inhibition of gastrointestinal motility, all of which accompany opiate use. Yet, these effects are not seen in runners. The most limiting factor, however, is that the endorphin hypothesis rests entirely on research measuring endorphins in circulating blood, as ethical reasons preclude the determination of central concentrations of endorphins. Because endorphins are too large to cross the blood-brain barrier, peripheral activation in the systemic circulation cannot be taken as indicative of central effects. In recent years, several prominent endorphin researchers—for example, Dr Huda Akil and Dr Solomon Snyder—have publicly criticised the hypothesis as being “overly simplistic”, being “poorly supported by scientific evidence”, and a “myth perpetrated by pop culture.”

At first glance, it appears that the runner’s high phenomenon is, at present, not a scientific problem because it is built on circumstantial evidence and lacks a plausible mechanistic explanation. However, recent data in our laboratory showed that endurance exercise activates the endocannabinoid system, suggesting a new mechanism underlying exercise induced alterations of mental status. Using trained male college students running on a treadmill or cycling on a stationary bike for 50 minutes at 70-80% of maximum heart rate, we found that exercise of moderate intensity dramatically increased concentrations of anandamide in blood plasma. (Currently, research is underway in our laboratory to explore this finding further by examining

Abbreviations: 2-AG, sn-2-arachidonylglycerol; THC, tetrahydrocannabinol
the effect of exercise on both serum and cerebrospinal fluid concentrations of endocannabinoids in exercising rats, while also examining several associated alterations of behaviour.) Because activation of the endocannabinoid system reduces pain sensations and alters emotional and cognitive processes, this finding has implications for some of the psychological effects that accompany exercise. Owing to the presence of cannabinoid receptors in muscle, skin, endothelial cells, and lung, this finding also suggests a possible role for the endocannabinoid system in mediating certain physiological responses to exercise.

It is important to emphasize that the intention of this paper is not to substitute one neurotransmitter for another and perpetuate the simple reductionist idea of one neurochemical being responsible for a complex variety of psychological processes. Rather, we review the literature on the functional role of the endocannabinoid system as it relates to exercise and call attention to the possibility that the endocannabinoid system may play an important role in the physiological and psychological adaptations to exercise. The review opens unexpected and entirely novel avenues of research in exercise physiology and psychology and is offered on the strength of its heuristic value.

In addition, we propose to reconceptualise the runner’s high into a set of behavioural phenomena that can be, at least to a large extent, subjected to scientific scrutiny. Traditionally, the runner’s high has been operationally defined as a “euphoric sensation experienced during running, usually unexpected, in which the runner feels a heightened sense of well being, enhanced appreciation of nature, and transcendence of barriers of time and space” (Pargman et al, p 342). It is obvious that such a broad definition, in conjunction with the extensive use of esoteric language, does not qualify as an operational definition that can be used to derive testable hypotheses. We propose instead a more limited operational definition of the runner’s high centred mostly on observable behaviours such as analgesia, sedation (post-exercise calm), anxiolysis, and a sense of wellbeing. This definition has a number of advantages. Firstly, there is a large body of scientific literature documenting that exercise suppresses pain, induces sedation, reduces stress, and elevates mood. Secondly, because these effects are directly measurable, the operational definition allows the formulation of empirical predictions and the testing of specific hypotheses. Moreover, data from animal research can be recruited to elucidate the phenomena, as exercise in rodents has been shown to increase tolerance of pain (hot plate or tail flick tests), induce sedation (open field test), and produce anxiolysis (elevated plus maze).

**THE ENDOCANNABINOID HYPOTHESIS**

Endocannabinoid receptors and their endogenous ligands have been identified. To date, two cannabinoid receptor subtypes have been cloned. The CB1 receptor is located in the central nervous system, and it is more densely concentrated on the membranes of neurons located in the cortex, hippocampus, basal ganglia, amygdala, hypothalamus, and cerebellum. CB1 receptors are also found in several peripheral sites, including the peripheral nervous system. The CB2 receptor, on the other hand, is located mainly in peripheral tissue. Both the CB1 and CB2 receptors are coupled to Gi/o proteins. Thus cannabinoid receptors inhibit adenylate cyclase and, thereby, depending on the cell type, either inhibit voltage gated calcium channels or activate potassium channels. Thus, with respect to the nervous system, the general effect of CB1 activation is neuronal inhibition, which does not apply to CB2 receptors, as they are mainly expressed on immune cells. There is also an ongoing hypothesis in the field that there may exist an additional cannabinoid receptor, tentatively named CB3. Although the existence of a CB3 receptor is currently hypothetical, it may be of interest as some of the effects reported in this review might turn out not to be accounted for by CB1 and CB2 receptors.

Two naturally occurring ligands, which are members of a small family of fatty acid derivatives, have been identified for CB1 and CB2 receptors. Anandamide is one ligand, and it exhibits a higher affinity for the CB1 receptor subtype than CB2. A second ligand, 2-arachidonylglycerol (2-AG), has been identified more recently. Although the two endocannabinoids are found in the systemic circulation at equal concentrations, the concentration of 2-AG is about 200 times higher than that of anandamide in the brain. Anandamide and 2-AG have different biosynthetic pathways and may be produced under different conditions. However, the sites of anandamide and 2-AG production in brain and peripheral tissues are not known. Because endocannabinoids are lipids that are rapidly eliminated from extracellular space, it is generally assumed that production sites are located in close proximity to their attending cannabinergic receptors. More importantly, the environmental stimuli responsible for the production and release of endocannabinoids are also unknown, making it difficult to assess the physiological and behavioural functions of anandamide and 2-AG.

**Cannabinoids and exercise induced analgesia**

The role of the endocannabinoid system as an alternative neuromodulatory system in pain perception has been a central focus of cannabinoid research. Analgesia is mediated in part by the endogenous opioid system. However, analgesia that is insensitive to opioid antagonists can also occur, providing evidence for non-opioid antinociception. Using animal models of acute and tonic pain, behavioural studies with a wide variety of noxious stimuli have shown cannabinoid induced antinociception, which is mediated by CB1 receptors. The potency and efficacy of cannabinoids in producing antinociception rival that of morphine.

Unlike opioid mediated suppression of pain neurotransmission, the endocannabinoid system has been shown to suppress pain not only at central, but also at peripheral concentrations. CB1 receptors are densely expressed on peripheral nerve terminals such as pain sensing C (small diameter) fibres, large diameter Aβ and Aδ fibres, as well as in the dorsal root ganglia. Cannabinoids also act at central sites to modulate pain sensitivity. For example, cannabinoid receptors in the dorsal horn of the lumbar spinal cord have been shown to attenuate pain evoked by noxious heat applied to rat hind paw. In the brain, Meng et al found a brainstem circuit involving the rostral ventromedial medulla that is activated by cannabinoids. Although activation of neurones in the rostral ventromedial medulla is also required for the alarmic effects of morphine, the cannabinoids modulate its activity independently, demonstrating a separate central mechanism of action for antinociception. The cannabinoids also affect pain perception by acting in the periaqueductal gray system, an area dense in opioid receptors. Electrical stimulation of the dorsal and lateral periaqueductal gray system produces analgesia that is both CB1 receptor mediated and accompanied by the release of anandamide in the system. Finally, subcutaneous injection of the chemical irritant formalin triggers an increase of anandamide in the periaqueductal gray system, further implicating the endocannabinoids not only in the modulation of chemogenic pain, but also more generally in the centrally mediated suppression of pain.
receptor antagonist, induces withdrawal in cannabinoid dependent rats, whereas administration of the CB1 receptor antagonist SR141716A precipitates withdrawal in morphine dependent rats.40

With regard to exercise induced analgesia, there are some significant differences between opioid and cannabinoid antinociception. Firstly, cannabinoids produce analgesia by acting at a number of peripheral sites.14 15 Although endocannabinoids such as anandamide are lipids and can cross the blood-brain barrier readily, this is not a requirement for the analgesic properties of endocannabinoids. This fact avoids one of the principal problems that plagued the endorphin hypothesis of exercise induced analgesia. Secondly, because of its highly lipophilic properties, systemic increases in anandamide concentrations are generally assumed to produce central effects. Consequently, in addition to peripheral sites, the increase in blood anandamide concentrations in endurance athletes is likely to activate analgesic systems in the brain. Finally, as mentioned above, subcutaneous injections of the chemical irritant formalin into rat hind paw increases the release of anandamide in the periaqueductal gray system,39 showing that noxious agents can produce analgesia at central sites without the activation of peripherally circulating endocannabinoids.

Research on cannabinoid induced analgesia has made use of a variety of noxious stimuli, and it has become clear that different types of tissue damage (mechanical, thermal, chemical, etc) differentially activate the endocannabinoid system.14 19 20 The finding that there are particular types of pain against which cannabinoids are particularly effective may provide fresh insights into the sport specificity of the runner’s high. It is curious that an “exercise high”, similar to the one experienced by long distance runners, should not occur in athletic activities involving brief physical exertion, such as sprinting and weightlifting, or in sports requiring changes in pace and workload such as track, soccer, football, tennis, basketball, etc. Further testing should resolve the issue whether these activities engage the endocannabinoid system.14 19 20 The finding that there are particular types of pain against which cannabinoids are particularly effective may provide fresh insights into the sport specificity of the runner’s high. It is curious that an “exercise high”, similar to the one experienced by long distance runners, should not occur in athletic activities involving brief physical exertion, such as sprinting and weightlifting, or in sports requiring changes in pace and workload such as track, soccer, football, tennis, basketball, etc. Further testing should resolve the issue whether these activities engage the endocannabinoid system.

Yet, there is also no reference to a “swimmer’s high” in the literature, although it is a rhythmic and repetitive activity producing a particular pain concentration at a specific heart rate. Bearing on this problem, evidence is accumulating that cannabinoids induce analgesia by acting through CB1 receptors located in skin.17 19 41 This mechanism might suggest that painful stimuli to the skin are particularly potent in activating endocannabinoid antinociception. Unlike other rhythmic endurance activities such as swimming, running is a weight bearing sport in which the feet must absorb the “pounding of the pavement.” We are not arguing that moderate intensity long distance swimming fails to activate the endocannabinoid system. Rather, an endurance activity of this nature may not stimulate endocannabinoid release to as great an extent as running.

It is also important to mention with regard to the runner’s high that cannabinoids produce neither the respiratory depression, miosis, or strong inhibition of gastrointestinal motility associated with opiates and opioids. This is because there are few CB1 receptors in the brainstem19 and, apparently, the large intestine.

Finally, anandamide also inhibits oedema and inflammation,13 and low doses of cannabinoids of insufficient magnitude to produce analgesia or motor impairment14 attenuate chemogenic pain.44 This observation is also relevant to exercise induced analgesia, as muscle pain is believed, in part, to be the result of the generation of substances such as lactic acid.45

Psychoactive effects of cannabinoids

The psychoactive constituent of marijuana, Δ(9)-tetrahydrocannabinol (THC), exhibits high affinity for the CB1 receptor, which is densely expressed in brain regions implicated in the control of emotion and cognition.29 42 This distribution provides the basis for the profound psychological effects of exogenous cannabinoids. A prominent effect of cannabinoids is the induction of sedation. In addition, cannabinoids are reported to reduce anxiety,29 alter attention,45 and impair both working memory46 and spatial learning,57 apparently by interfering with hippocampus dependent neuronal processes responsible for declarative memory.58 Users of marijuana often report distortions of time estimation,59 euphoria and enhanced sensory perception,52 a state of silent introspection, and feelings of wellbeing.19 45 Cannabinoids exert a negative effect on dopaminergic activity in the prefrontal cortex.52 For example, treatment with THC results in a change in regional cerebral blood flow in the rat. In particular, decreases have been measured to the hippocampus and the frontal and medial prefrontal cortices. However, changes have not been found in the ventral tegmentum, caudate nucleus, cerebellum, temporal cortex, parietal cortex, or occipital cortex.53 Likewise, as evidenced by functional nuclear magnetic resonance imaging, chronic marijuana users show decreased activity of the dorsolateral prefrontal cortex, an area highly associated with working memory.54 A decrease in prefrontal cortex metabolism has also been shown in rats chronically exposed to THC.55 It has been suggested56 that hypometabolism in prefrontal cortical regions may contribute significantly to the impaired cognitive processes associated with cannabinoid use.

Administration of the endogenous cannabinoid anandamide, which also binds to CB3 receptor, elicits similar effects to those produced by THC.57 Although some pharmacological differences exist between the plant derived THC and anandamide, systematic structure-activity relation studies have shown that the two compounds act at the CB3 receptor in a similar manner.58

The intense psychological experiences elicited by the activation of the endocannabinoid receptors are strikingly similar to the experience of the runner’s high. To compare, the mental changes that accompany long distance running include analgesia, sedation (post-exercise calm or glow), a reduction in anxiety, euphoria, and difficulties in estimating the passage of time.19 20 In addition, a recent study investigating higher cognitive functioning during exercise has shown that prolonged running and cycling produces deficiencies in prefrontal dependent cognitive processes such as sustained attention and working memory.57 One possible explanation of these findings may be that the increased endocannabinoid release during exercise results in diminished metabolism in prefrontal regions while at the same time altering cognitive function and consciousness. Although such parallels are anecdotal and speculative, such comparisons have shed light on psychological and pharmacological phenomena in the past. As with the mental changes associated with long distance running, most of the behavioural effects of the cannabinoids depend on set and setting.

Cannabinoids and motor behaviour

The highest concentration of CB1 receptors in the brain can be found in the basal ganglia, particularly in output nuclei, and the cerebellum, implicating the endocannabinoid system in the control of movement.29 42 Indeed, there is substantial evidence that cannabinoids affect motor behaviour.42 43 45

In a variety of species including humans, administration of plant derived endogenous and synthetic cannabinoids produces biphasic effects on locomotion.41 In larger doses, cannabinoid agonists produce well known and profound motor inhibition. Thus, as might be expected, cannabinoids have proven clinically useful in treating movement disorders such as tics, dyskinesia, tremors, and dystonia.40 50 These
The cannabinoids produce psychological states that closely parallel several experiences described as being related to the runner’s high. Compared with the opioid analgesics, the analgesia produced by the endocannabinoid system is more consistent with exercise induced analgesia. Activation of the endocannabinoid system appears to facilitate breathing during exercise.

**Peripheral effects**

Activation of the endocannabinoid system may also participate in other adaptive responses to exercise. For instance, endocannabinoids act as a vasodilator and produce hypotension, and may thus facilitate blood flow during exercise. Although the distribution of CB1 receptors in smooth muscle and endothelial cells suggests that the vasorelaxant effects of anandamide are mediated through CB1 receptors, recent experiments have implicated a prominent role of vanilloid receptors in the vasodilatory effects of these endocannabinoids. Finally, cannabinoids affect the respiratory system. Although studies have reported bidirectional control of airway responsiveness, in general, endocannabinoids and exogenous cannabinoids act as bronchodilators.

**Conclusions**

To date, a sound neural mechanism for the well known beneficial effects of exercise on mental health has yet to be proposed. Recent findings show that exercise increases serum concentrations of endocannabinoids, a result suggestive of a new possible explanation for a number of these changes. Further research is necessary to characterise the precise nature of this endocannabinoid response to exercise, specifically the relative importance of factors such as the nature of the activity, exercise duration, exercise intensity, sex, and age. In addition, animal models can be used to identify the production and binding sites of endocannabinoids as well as their functional role in exercise.
endocannabinoid system also produces sedation, anxiolysis, a sense of wellbeing, reduced attentional capacity, impaired working memory ability, and difficulty in time estimation. This behavioural profile is similar to the psychological experiences reported by long distance runners. Considerable research is needed to clarify to what extent the endocannabinoid system might be responsible for the exercise induced changes in mental status. Nevertheless, a significant upregulation of serum concentrations of endocannabinoids has recently been reported in endurance athletes, and studies are underway to explore this further in laboratory animals.

The close interaction of endocannabinoids with dopamine shows that they have a function in the brain’s reward system and therefore possibly addiction. The endocannabinoid system might be responsible for the exercise induced changes in mental status. Considerable research is needed to clarify to what extent the endocannabinoid hypothesis is a feasible alternative to the endorphin hypothesis and should be subjected to further empirical tests.

Finally, the endocannabinoid system mediates peripheral effects such as vasodilation and bronchodilation that may play a contributory role in the body’s response to exercise. This article is intended to provide an overview of the emerging field of the endocannabinoid-exercise interaction. The list of topics was necessarily selective, but it is offered in the hope that researchers of diverse backgrounds will use the review to conduct empirical tests of its premises. We suggest that the “endocannabinoid hypothesis” is a feasible alternative to the endorphin hypothesis and should be subjected to further empirical tests.

Authors’ affiliations
A Dietrich, Department of Social and Behavioral Sciences, American University of Beirut, Lebanon
WF McDaniel, Georgia College and State University, Milledgeville, GA, USA

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Correlations between plasma noradrenaline concentrations, antioxidants, and neutrophil counts after submaximal resistance exercise in men
A Ramel, K-H Wagner, J Elmadfa

Background: Generation of reactive oxygen species (ROS) during exercise has been linked to increased oxygen consumption. ROS could also be produced by other mechanisms—for example, a respiratory burst of neutrophils or catecholamine auto-oxidation—when oxygen consumption is only moderately increased.

Objectives: To investigate noradrenaline concentrations, neutrophil counts, plasma antioxidants, and lipid oxidation products before and after acute resistance exercise.

Methods: 17 male participants undertook a submaximal resistance exercise circuit (10 exercises; 75% of the one repetition maximum; mean (SD) exercise time, 18.6 (1.1) minutes). Blood samples were taken before and immediately after exercise and analysed for plasma antioxidants, noradrenaline, neutrophils, and lipid oxidation products. Wilcoxon’s signed-rank test and Pearson’s correlation coefficient were used for calculations.

Results: Neutrophils, noradrenaline, fat soluble antioxidants, and lipid oxidation products increased after exercise. Noradrenaline concentrations were associated with higher antioxidant concentrations. Neutrophils were related to higher concentrations of conjugated dienes.

Conclusions: Submaximal resistance exercise increases plasma antioxidants. This might reflect enhanced antioxidant defence in response to the oxidative stress of exercise, though this is not efficient for inhibiting lipid oxidation. The correlation between noradrenaline concentrations and plasma antioxidants suggests modulating role of the stress hormone. Neutrophils are a possible source of oxidative stress after exercise.

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