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 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, confounding 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.

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\textsuperscript{16} and alters emotional and cognitive processes,\textsuperscript{17} this finding has implication for some of the psychological effects that accompany exercise. Owing to the presence of cannabinoid receptors in muscle, skin, endothelial cells, and lung,\textsuperscript{18,19} this finding also suggests a possible role for the endocannabinoid system in mediating certain physiological responses to exercise.

It is important to emphasise 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 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,\textsuperscript{20} induces sedation,\textsuperscript{21} reduces stress,\textsuperscript{22} and elevates mood.\textsuperscript{23} 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.\textsuperscript{24–28} To date, two cannabinoid receptor subtypes have been cloned. The CB\textsubscript{1} receptor is located in the central nervous system, and it is more densely concentrated on the membranes of neurones located in the cortex, hippocampus, basal ganglia, amygdala, hypothalamus, and cerebellum.\textsuperscript{29–31} CB\textsubscript{1} receptors are also found in several peripheral sites, including the peripheral nervous system.\textsuperscript{32} The CB\textsubscript{2} receptor, on the other hand, is located mainly in peripheral tissue. Both the CB\textsubscript{1} and CB\textsubscript{2} receptors are coupled to G\textsubscript{i/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.\textsuperscript{33} Thus, with respect to the nervous system, the general effect of CB\textsubscript{1} activation is neuronal inhibition, which does not apply to CB\textsubscript{2} 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 CB\textsubscript{3}.\textsuperscript{34} Although the existence of a CB\textsubscript{3} 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 CB\textsubscript{1} and CB\textsubscript{2} receptors.

Two naturally occurring ligands, which are members of a small family of fatty acid derivatives, have been identified for CB\textsubscript{1} and CB\textsubscript{2} receptors. Anandamide is one ligand, and it exhibits a higher affinity for the CB\textsubscript{1} receptor subtype than CB\textsubscript{2}.\textsuperscript{35} A second ligand, sn-2-arachidonoylglycerol (2-AG), has been identified more recently.\textsuperscript{36} 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.\textsuperscript{37} Anandamide and 2-AG have different biosynthetic pathways and may be produced under different conditions.\textsuperscript{38} 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 cannabergic 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.\textsuperscript{39–41} 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 cannabionoid induced antinociception,\textsuperscript{42} which is mediated by CB\textsubscript{2} receptors.\textsuperscript{43} The potency and efficacy of cannabinoids in producing antinociception rivals 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.\textsuperscript{44,45} CB\textsubscript{3} receptors are densely expressed on peripheral nerve terminals such as pain sensing C (small diameter) fibres, large diameter A\textsubscript{B} and A\textsubscript{a} fibres, as well as in the dorsal root ganglia.\textsuperscript{46,47} Cannabinoids also act at central sites to modulate pain sensation. 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.\textsuperscript{48} In the brain, Meng et al.\textsuperscript{49} 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 analgesic 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.\textsuperscript{50} Electrical stimulation of the dorsal and lateral periaqueductual gray system produces analgesia that is both CB\textsubscript{1} 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.\textsuperscript{51}

Cannabinoids and opioids also exhibit synergistic effects in the production of antinociception, and bidirectional interactions between opioid and cannabinoid dependence have been reported. For example, administration of naloxone, a opioid
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,19 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. Yet, there is also no reference to a “swimmer’s high” in the literature, although it is a rhythmic and repetitive activity of this nature may not stimulate 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 brainstem and, apparently, the large intestine.

Finally, anandamide also inhibits oedema and inflammation,21 and low doses of cannabinoids of insufficient magnitude to produce analgesia or motor impairment22 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.26

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 32 This distribution provides the basis for the profound psychological effects of exogenous cannabinoids. A prominent effect of cannabinoids is the induction of sedation.15 In addition, cannabinoids are reported to reduce anxiety,43 alter attention,43 and impair both working memory46 and spatial learning.47 48 Apparently by interfering with hippocampus dependent neuronal processes responsible for declarative memory.48 Users of marijuana often report distortions of time estimation,50 euphoria and enhanced sensory perception,51 a state of silent introspection, and feelings of wellbeing.44 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 differential with cannabinoid use.

Administration of the endogenous cannabinoid anandamide, which also binds to CB1 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 CB1 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.15 22 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 32 Indeed, there is substantial evidence that cannabinoids affect motor behaviour.42 43 59

In a variety of species including humans, administration of plant derived endogenous and synthetic cannabinoids produces biphasic effects on locomotion.15 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.60 61 These
effects are reversed by administration of the selective CB₁ receptor antagonist SR141716A, providing evidence that cannabinoids mediate motor activity through the CB₁ receptor. In low doses, however, cannabinoids tend to produce hyperactivity. For example, intracerebroventricular injection of low doses of anandamide increased locomotion, and systemic injections of low doses of anandamide stimulated behavioural activity in the open field. Finally, CB₁ knockout mice are extremely hypomorphic, suggesting that one of the principal physiological roles of the endocannabinoid system may be the refinement of movements needed for coordinated locomotion.

Cannabinoids appear to modulate motor behaviour by altering the transmission of other transmitter systems in the basal ganglia. They appear to increase γ-aminobutyric acid transmission (although this remains controversial), inhibit glutamate transmission, and inhibit the reuptake of dopamine. In addition, anandamide release in the dorsal striatum increases in freely moving rats, and it has been suggested that it acts as a striatal neurotransmitter in its own right (for a thorough review, see Piomelli). It is worth noting that the basal ganglia have been implicated in the control of movements based on well learned motor behaviour. The more a motor skill is practiced and becomes automatic, the more the details of its execution come under the control of the basal ganglia. Hence, we predict that lower level skills such as running, which are controlled to a higher degree by the basal ganglia than high level skills, such as basketball, hockey, or tennis, may more readily activate the endocannabinoid system.

Cannabinoids and addiction

There is also a close interaction between dopamine and the endocannabinoid system in structures that are implicated in the brain’s reward system. The dopamine D₁ and D₂ receptors are colocalised with the CB₁ receptor, and it has been shown that the cannabinoids alter dopaminergic activity in the medial forebrain bundle. Cannabinoids increase the firing rates of dopaminergic neurones in the ventral tegmentum, substantia nigra, and the medial forebrain bundle. Withdrawal from cannabinoids, on the other hand, results in a decline in dopaminergic activity in the medial forebrain bundle. Projections from the ventral tegmentum to the nucleus accumbens via the median forebrain bundle mediate the rewarding effects of most drugs of abuse, and the reinforcer properties of endocannabinoids and cannabinoids appear to be mediated through this pathway. Evidence now supports the hypothesis that both endocannabinoids and exogenous cannabinoids induce a selective release of dopamine in the shell of nucleus accumbens through CB₁ receptors. This evidence also suggests that the activation of endogenous cannabinoids through exercise could account for exercise addiction. It also follows that pretreatment with selective dopamine or endocannabinoid receptor antagonists should block induction of an exercise induced high. These possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve scientific inquiry, although the ethics of such studies in humans would bring into question morale possibilities deserve 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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 is also implicated in the control of motor activity and may play a contributory role in the body’s response to exercise. Effects such as vasodilation and bronchodilation that may system is also implicated in the control of motor activity and psychological mood alterations: effects of prolonged exercise. The second wind. In: Sacks MH, Sachs ML, eds. The list of topics was necessarily selective, but it is offered in hope that researchers of diverse backgrounds will use the endocannabinoid hypothesis and should be subjected to further empirical tests. The close interaction of endocannabinoids with dopamine suggests that the “endocannabinoid hypothesis” is a feasible alternative to the endorphin hypothesis and should be subjected to further empirical tests.

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Correlations between plasma noradrenaline concentrations, antioxidants, and neutrophil counts after submaximal resistance exercise in men

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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 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 a modulating role of the stress hormone. Neutrophils are a possible source of oxidative stress after resistance exercise.

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Are sports medicine journals relevant and applicable to practitioners and athletes?

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Objective: To examine whether sports medicine journals are relevant and applicable to daily practice.

Methods: Original research articles, short reports, and case reports published in four major sport and exercise medicine journals were reviewed. Journal contents were classified according to main topic of study and type of subjects used.

Results: The most common topic was sports science, and very few studies related to the treatment of injuries and medical conditions. The majority of published articles used healthy subjects sampled from the sedentary population, and few studies have been conducted on injured participants.

Conclusions: There is a need for Diagnostic and treatment interventions in the sports medicine literature. The evidence base for sports medicine must continue to increase in terms of volume and quality.