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Brief Review

Abdominal fat-reducing outcome of exercise training: Fat burning or hydrocarbon source redistribution?

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Running title: Fat burning concept may be wrong

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Abstract

Fat burning, defined by fatty acid oxidation into carbon dioxide, is the most described hypothesis to explain the actual abdominal fat-reducing outcome of exercise training. This hypothesis is strengthened by evidence of increased whole-body lipolysis during exercise. As a result, aerobic training is widely recommended for obesity management. This intuition raises several paradoxes: First, both aerobic and resistance exercise training do not actually elevate 24-h fat oxidation, according to data from chamber-based indirect calorimetry. Second, anaerobic high-intensity intermittent training produces greater abdominal fat reduction than continuous aerobic training at similar amounts of energy expenditure. Third, significant body fat reduction in athletes occurs when oxygen supply decreases to inhibit fat burning during altitude-induced hypoxia exposure at the same training volume. Lack of oxygen increases post-meal blood distribution to human skeletal muscle, suggesting that shifting the postprandial hydrocarbons towards skeletal muscle away from adipose tissue might be more important than fat burning in decreasing abdominal fat.

Conclusion: Creating a negative energy balance in fat cells due to competition of skeletal muscle for circulating hydrocarbon sources may be a better model to explain the abdominal fat-reducing outcome of exercise than the fat burning model.

Keyword: obesity, anaerobic exercise, weight training, high intensity intermittent training, dual-energy X-ray absorptiometry (DEXA)
Basal metabolism accounts for approximately 50-70% of daily energy intake in the average adult, where most of energy required for ATP production at rest comes from fatty acid oxidation. Before meals, fatty acid and glycerol concentrations in the abdominal venous blood are three fold greater than those in the forearm venous blood (Coppack et al. 1990), suggesting that abdominal fat cells are continuously exporting fatty acids into circulation and that skeletal muscle is a major consumer of this hydrocarbon source (Figure 2A). The concentration differences of venous fatty acids and glycerol between abdominal and forearm blood diminishes to nearly zero for a very brief period approximately 1 hour after meal. If the human body is continuously dumping fatty acids out of fat cells as a 24-h routine, why do so many sedentary individuals still become obese? Since both muscle and adipose tissues possess a high capacity to uptake and store hydrocarbons from multiple sources (fat, carbohydrate, and protein), the relative distribution of postprandial hydrocarbon sources to fat versus skeletal muscle tissues is undoubtedly an important determinant for the size of the abdominal fat cells. In support of this idea, several animal experiments have demonstrated that the size of adipose tissue is dictated by muscles. Expanding muscle size, using myostatin inhibition (Guo et al. 2006) and c-ski overexpression (Diaz et al. 2012), consistently results in lower body fat mass. Taken together, increasing the skeletal muscle demand on circulating hydrocarbons is a key factor in preventing abdominal obesity in adults (Figure 2B and 2C).

The effect of exercise-induced increases in fuel extraction of skeletal muscle appears to be ephemeral (Levenhagen et al. 2001). Exercise acutely increases insulin sensitivity of contracted skeletal muscle (Ivy and Kuo 1998), which is partly associated with increased glycogen storage compared to non-exercised muscle (Kuo et al. 1999). Delaying meal supplementation after exercise attenuates increases in
glycogen storage (Ivy et al. 1988) and glucose uptake in exercised leg (Levenhagen et al. 2001), which also leads to less effective fat decreases by exercise training (Suzuki et al. 1999; Trapp et al. 2008). Therefore, workout schedule in relation to meal time, particularly when circulatory hydrocarbon sources are surging before being partitioned to adipose tissues, would be crucial to maximize the negative balance of abdominal fat cells for triglyceride storage. This concept is supported by evidence from a randomized study in which weight-trained men consuming a meal immediately before and after training demonstrated a greater decrease in fat mass and an increase in lean body mass compared to consuming a meal in the early morning and late evening (Cribb and Hayes 2006). Similar to this human trial, delaying meals in animals for 4 hours after exercise training results in greater fat accumulation and less muscle mass compared to animals receiving a meal immediately after exercise (Suzuki et al. 1999).

In addition, the lipoprotein lipase activity ratio of adipose tissue versus skeletal muscle in trained individuals increases approximately 8-fold when their lifestyle shifts from active to inactive (Simsolo et al. 1993). Lipoprotein lipase (LPL) is a capillary-embedded enzyme responsible for the hydrolysis of circulating triglycerides into fatty acids, which is an essential step for the partitioning of hydrolyzed fatty acids into local tissues when triglyceride is delivered by blood. This evidence suggests that the distribution of fatty hydrocarbons is more likely to be distributed to adipose tissue than muscle when an individual’s lifestyle becomes more sedentary. Thus, we would expect greater distribution of fatty hydrocarbons to abdominal fat compared to skeletal muscle still persists regardless of whether the amount of food is reduced or type of hydrocarbons (carbohydrate versus fat) is altered as an individual becomes more sedentary.
In contrast to the proposed “hydrocarbon source redistribution hypothesis”, the deeply rooted “fat-burning hypothesis” receives weaker support from scientific evidence to explain the actual fat-reducing outcomes of exercise training. Implicit to the fat burning concept is that increased energy consumption by muscle contraction can be translated into greater fatty acid oxidation into carbon dioxide, resulting in the observed abdominal fat reducing outcomes of exercise training. This concept creates a number of paradoxes. The most important evidence against this “fat-burning hypothesis” comes from a study using indirect calorimetry in a respiration chamber. This study shows no difference in 24-h fatty acid oxidation between sedentary and exercise conditions (Melanson et al. 2002b). Furthermore, exercise does not increase 24-h fatty acid oxidation when energy balance is maintained (Melanson et al. 2009). Both aerobic endurance training and anaerobic weight training do not appear to increase 24-h fatty acid oxidation (Melanson et al. 2002a) (Figure 1C). Nevertheless, both types of exercise regimens have been repeatedly demonstrated to decrease abdominal body fat at sufficient exercise intensity (Toth et al. 1999). As exercise intensity increases from the sedentary state, the human body increasingly becomes anaerobic and dependent more on carbohydrate (particularly the glycogen stored in skeletal muscle) as a fuel, with a concomitant decrease in energy dependence from plasma fatty acid (produced mainly from adipose tissue) (Romijn et al. 1993). Apparently, aforementioned scientific experiments reject the fat burning hypothesis. Based on fat burning hypothesis, conventional recommendations have been focused more on low intensity aerobic exercise for preventing obesity. However, a recent systemic review has concluded that low intensity exercise training is less effective in reducing body fat than moderate to high intensity exercise training (Tremblay et al. 1994; Vissers et al. 2013). The most noteworthy report comes from another recent
systemic review on the effect of high intensity intermittent exercise (HIIT) on fat loss (Boutcher 2011). It is generally known that HIIT is purely anaerobic exercise training. However, abdominal fat reduction after HIIT can be achieved to a level between 40-50% in patients with metabolic disorders (Boudou et al. 2003; Mourier et al. 1997). Furthermore, 10-week HIIT (anaerobic in nature) decreases more total body fat and trunk fat than 40-min of continuous aerobic exercise at 60% VO$_{2\text{peak}}$, when energy expenditure and weekly frequency are comparable (Trapp et al. 2008). Moderate intensity of aerobic exercise around 60% VO$_{2\text{peak}}$ is widely recommended based on fat-burning hypothesis. Nevertheless, we should always be aware that total volume of exercise is still important for the fat reducing outcome of exercise training. This is indicated by the dose-dependency of abdominal fat-reducing outcome of exercise training based on two well-conducted systemic reviews (Ross and Janssen 2001; Slentz et al. 2009).

In compliance with the second law of thermodynamics, exercise is a stress that increases the entropy of the cell, a highly ordered molecular aggregate. To bring a challenged cell or tissue back to a stable condition, damaged and energy-depleted muscle fibers will have to demand more postprandial hydrocarbon species compared with adipose tissues, leading to whole-body hydrocarbon source redistribution and resulting in a more favorable body composition. To explain the discrepancy between the actual fat reducing effects of exercise training in absence of increased 24-h fatty acid oxidation (Melanson et al. 2002b), it is likely that not all degraded hydrocarbon sources (acetyl-CoA and ketones from glucose and fatty acid) during exercise are converted to carbon dioxide for ATP resynthesis during and after exercise. That is, exercise increases lipolysis (hydrolysis of triglyceride to fatty acid and glycerol) (Romijn et al. 1993), but not necessarily converts all fatty acid into carbon dioxide.
when amount of oxygen is not sufficient to allow complete electron transport and citric acid cycle. Some degraded hydrocarbon species may be recycled into challenged muscle tissues, where reconstruction is in high demand. Most of the hydrocarbon sources (fat, carbohydrate, and protein) in living cells are interconvertible via a variety of enzymatic reactions and can be redistributed via the circulation in the human body. Fatty acid is the richest hydrocarbon source of acetyl-CoA, a building block of a wide range diffusible hydrocarbon sources such as ketones, cholesterol, amino acids, and fatty acids. Tissue growth is probably the most powerful magnet for hydrocarbon source settlement, which may cause a reciprocal size reduction of other tissues. Phenomenon such as tumor growth with reciprocal fat and muscle loss (adipopenia and sarcopenia) in humans suggests that hydrocarbon sources are able to redistribute in a living multicellular organism (Fouladiun et al. 2005). To support the concept of ectopic influence on fat deposition by other tissues, we have recently found that both the levels of extracellular and intracellular myocellular lipids in the sedentary leg can be influenced by activity levels of the contralateral leg in healthy men (Zhu et al. 2015). Increasing muscle growth would be more likely to occur after high-intensity exercise than moderate exercise simply due to more cell regeneration is needed after greater muscle damage. This may therefore be a reasonable explanation for the fact that high intensity exercise training, despite its anaerobic nature, provides a greater fat reducing effect than low-intensity aerobic exercise (Trapp et al. 2008; Vissers et al. 2013).

We previously conducted a human trial to test the hypothesis that fat burning is essential for maintaining low body fat in training athletes (Chia et al. 2013). Since fat burning cannot occur without oxygen, we would expect that decreasing oxygen availability at altitude should lead to body fat accumulation. To test this concept,
swimmers \((n=10)\) were moved from sea-level to an altitude training camp at 2300 meters to decrease oxygen availability, while a constant training volume of 12.3 km/day was maintained. Three weeks later, the body weight of these athletes was unaltered; meaning that the total hydrocarbon amount in the body was unchanged. In contrast to the sea-level counterparts \((n=8)\), body fat (measured by DEXA) in all of the swimmers was unequivocally decreased and muscle mass was increased following altitude hypoxia exposure. The results of this study reject the fat burning hypothesis as we have proposed. Furthermore, in order to determine the effects of hypoxia on muscle blood distribution during meal time, total hemoglobin concentration (THC) was traced by near-infrared spectroscopy (NIRS) in the triceps and quadriceps muscles under glucose-ingested and insulin-secreted conditions during hypoxia exposure \((16\% \text{ O}_2)\) after exercise training. Small decreases in blood oxygen saturation under such hypoxic conditions \((97\% \text{ versus } 93\%)\) resulted in an increased blood distribution to skeletal muscle (Chia et al. 2013). Since glucose and insulin are carrying by blood, hypoxia would favor fuel deposition to muscle tissue versus adipose tissue (Deveci et al. 2001). Therefore, regulating the balance of relative hydrocarbon redistribution towards either adipose tissue or skeletal muscle may be a more important mechanism in determining body composition than fat burning.

In conclusion, the abdominal fat-reducing outcome of exercise training may be associated with greater partitioning of hydrocarbon-based nutrients into skeletal muscle, which results in a negative energy balance of abdominal fat cells. This hydrocarbon redistribution hypothesis provides a reasonable interpretation to better explain the abdominal fat reducing outcome of high-intensity workouts in which there is more muscle fiber recruitment than in low-intensity workouts. The fat burning theory, referring to increased conversion of abdominal fat into carbon dioxide via...
oxidation during and after exercise, is not uniformly backed up by scientific evidence and such concept may lead to less effective recommendations for abdominal fat reduction regarding the type of exercise.

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References:


Figure legend

Figure 1. Fat-burning (fatty acid oxidation into carbon dioxide) cannot perfectly explain fat-reducing outcome of exercise training. Despite moderate-to-high intensity exercise is more effective in decreasing abdominal fat than low intensity exercise and rest (Vissers et al. 2013), relative energy contribution from fat during exercise decreases as intensity increases (A). Abdominal adipose tissue is the major supplier of plasma fatty acid, yet absolute energy contribution of plasma fatty acid decreases as exercise intensity increases (B) (Romijn et al. 1993). Both aerobic exercise and anaerobic resistance exercise increase 24-h total energy consumption, but both types of exercise do not increase the amount of 24-h fat burning (C) (Melanson et al. 2002a).

Figure 2. Skeletal muscle dictates fat cell mass. Before meal, lipolysis of abdominal fat tissue is continuously occurring, and muscle is a major consumer of the fatty hydrocarbon source in human body (A) (Coppack et al. 1990). After meal, hydrocarbon source from intestine replenishes triglyceride storage in adipose tissue, stimulated by insulin (B). Exercised muscle will demand more hydrocarbon source for fuel replenishment and tissue repair after physical challenge, which therefore causes negative balance in adipose tissue (C) (Trapp et al. 2008).
Figure 1

(A) Fuel contribution (%)

(B) Contribution from plasma FFA (μmol/L)

(C) 24-h Fatty acid oxidation (g/day)

Legend: □ Fat, □ Carbohydrate, □ Protein

Intensity Levels: Low intensity, Moderate intensity, High intensity

Exercise Types: Non-exercise, Aerobic exercise, Resistance exercise

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Figure 2
142x89mm (300 x 300 DPI)