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HIGH-INTENSITY INTERVAL TRAINING: NEW INSIGHTS

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KEY POINTS

- High-intensity interval training (HIT) is characterized by repeated sessions of relatively brief, intermittent exercise, often performed with an "all out" effort or at an intensity close to that which elicits peak oxygen uptake (i.e., ≥90% of VO_2peak).
- Although usually associated with improved "sprint"-type performance, many studies have shown that HIT for several weeks improves markers of aerobic energy metabolism, such as maximal aerobic capacity and the maximal activities of mitochondrial enzymes.
- Recent evidence suggests that short-term HIT is a potent, time-efficient strategy to induce rapid metabolic adaptations that resemble changes usually associated with traditional endurance training.
- As little as six sessions of HIT over two weeks, or a total of only ~15 minutes of very intense exercise (a cumulative energy expenditure of ~600 kJ or ~143 kcal), can increase oxidative capacity in skeletal muscle and improve performance during tasks that rely mainly on aerobic energy metabolism.
- While the underlying mechanisms are unclear, metabolic adaptations to HIT could be mediated in part through signaling pathways normally associated with endurance training.

INTRODUCTION

Regular endurance training improves performance during tasks that rely mainly on aerobic energy metabolism, in large part by increasing the body's ability to transport and utilize oxygen and by altering substrate metabolism in working skeletal muscle (Saltin & Gollnick, 1983). In contrast, high-intensity "sprint"-type exercise training is generally thought to have less of an effect on oxidative energy provision and endurance capacity. However, many studies have shown that high-intensity interval training (HIT) — performed with sufficient volume for at least several weeks — increases peak oxygen uptake (VO_2peak) and the maximal activities of mitochondrial enzymes in skeletal muscle (Kubekeli et al., 2002; Laursen & Jenkins, 2002; Ross & Leveritt, 2001). Recent evidence suggests that many adaptations normally associated with traditional high-volume endurance training can be induced faster than previously thought with a surprisingly small volume of HIT. The present article briefly summarizes skeletal muscle adaptations to HIT and highlights recent work that sheds new light on the potency of HIT to induce rapid skeletal muscle remodeling and improve exercise capacity.

RESEARCH REVIEW

What is HIT?

Although there is no universal definition, HIT generally refers to repeated sessions of relatively brief, intermittent exercise, often performed with an "all out" effort or at an intensity close to that which elicits VO_2peak (e.g., ≥90% of VO_2peak). Depending on the training intensity, a single effort may last from a few seconds to several minutes, with multiple efforts separated by up to a few minutes of rest or low-intensity exercise. In contrast to strength training, in which brief, intense efforts are usually performed against a heavy resistance in order to increase skeletal muscle mass, HIT is normally associated with activities such as cycling or running and does not induce marked fiber hypertrophy (Ross & Leveritt, 2001). A common HIT intervention — and the model used in our recent studies (Burgomaster et al., 2005, 2006, 2007; Gibala et al., 2006) — is the Wingate Test, which involves 30 s of maximal cycling against a high braking force on a specialized ergometer. The task is very demanding, and power output typically falls by 25-50% over the course of the test as the subject becomes fatigued. Another common HIT strategy is training sessions that use repeated fixed-duration efforts at a relatively high constant workload (Talanian et al., 2007).

Skeletal Muscle Adaptations to HIT

Similar to traditional endurance training or strength training, the skeletal muscular adaptive response to HIT is highly dependent on the precise nature of the training stimulus, i.e., the frequency, intensity and volume of work performed. However, unlike the other two forms of exercise that primarily rely on either oxidative (endurance) or non-oxidative (strength) energy to fuel ATP provision, the bioenergetics of high-intensity exercise can differ markedly depending on the duration and intensity of each interval, the number of intervals performed, and the duration of recovery between efforts (Ross & Leveritt, 2001). For example, during a single 30-s "all out" burst of maximal cycling, approximately 20% of total energy provision is derived from oxidative metabolism (Parolin et al., 1999). However, if the exercise bout is repeated three times with 4 min of recovery between bouts, ATP provision during the third bout is derived primarily from oxidative metabolism (Parolin et al., 1999). The increased contribution from oxidative metabolism during repeated high-intensity efforts is attributable to both an increased rate of oxygen transport and utilization and a decreased ability to stimulate ATP production through the breakdown of phosphocreatine and glycogen (Parolin et al., 1999). High-intensity intermittent exercise is therefore unique because cellular energy during an acute bout or a given training session can be derived primarily from non-oxidative or oxidative metabolism. Consequently, HIT can elicit a broad range of physiological adaptations. The reader is referred elsewhere for comprehensive reviews that have summarized skeletal muscle adaptations to a prolonged period of HIT (Kubekeli et al., 2002; Laursen & Jenkins, 2002; Ross & Leveritt, 2001). The following sections briefly highlight some of the major metabolic and morphological adaptations to HIT and focus on recent studies that have examined rapid skeletal muscle remodeling after short-term HIT.

Improved performance of "sprints" or high-intensity exercise after HIT is related in part to increases in the maximal activities of several enzymes that regulate non-oxidative energy provision (Juel et al., 2006; Kubukeli et al., 2002; Ross & Leveritt, 2001). In terms of muscle fiber composition, several studies have reported shifts of Type I and Type IIx fibers to Type IIa fibers, similar to the general trend observed after both endurance and strength training, although this is not a universal finding (Kubukeli et al., 2002; Ross & Leveritt, 2001). HIT does not have a major effect on muscle size, especially compared to heavy resistance training, although there may be a modest but significant hypertrophy of both Type I and Type II fibers after many months of HIT (Ross & Leveritt, 2001).

It has long been recognized that HIT also has the potential to increase muscle oxidative capacity and exercise performance during tasks that mainly rely on aerobic energy metabolism (Saltin & Gollnick, 1983). For example, MacDougall et al. (1998) reported an increased VO_2peak and increased maximal activities of several mitochondrial enzymes after a Wingate-based HIT protocol in which subjects performed 4-10 intervals per day, three times per week for seven weeks. However, until recently little was known regarding the early time course and minimum volume of training necessary to elicit these adaptations, or the effect of HIT on metabolic control during aerobic-based exercise. To address these problems, we conducted a series of studies that examined rapid adaptations in oxidative energy metabolism and exercise capacity after short-term HIT (Burgomaster et al., 2005; 2006; 2007; Gibala et al., 2006). Our standard HIT protocol involved subjects repeating the Wingate Test four to six times — each repeat separated by 4 min of recovery — for a total of only 2-3 min of very intense exercise per training session, with three training sessions performed each week for two weeks. The most unique aspect of our work has been the very low training volume, equivalent to only ~15 minutes of very intense exercise or ~600 kJ (143 kcal) of total work. All studies were performed on healthy college-aged men and women who were habitually active but not engaged in any sort of structured training program.

Our studies have consistently found an increased muscle oxidative capacity (assessed using the maximal activity or protein content of mitochondrial enzymes such as citrate synthase and cytochrome oxidase) ranging from ~15-35% after six sessions of HIT over two weeks (Burgomaster et al., 2005; 2006; 2007). Surprisingly, only a few studies have directly compared changes in muscle oxidative capacity after interval versus continuous training in humans, with equivocal results (see references in Gibala et al., 2006). Moreover, every study that has examined muscle oxidative capacity after interval versus continuous exercise training has used a matched-work design in which total work was similar between groups. Recently, we directly compared changes in muscle oxidative capacity and exercise performance after low-volume sprint training and traditional high-volume endurance training. The sprint protocol was based on other studies from our laboratory (Burgomaster et al. 2005, 2006) and consisted of six sessions of brief, repeated 'all out' 30-s cycling efforts, interspersed with short recovery periods, over 14 days. The endurance protocol consisted of six sessions of 90–120 min of moderate-intensity cycling exercise, with 1–2 days of recovery interspersed between training sessions. As a result, subjects in both groups performed the same number of training sessions on the same days with the same number of recovery days; however, total training time commitment was 2.5 h and 10.5 h, respectively, for the sprint and endurance groups, and training volume differed by 90% (630 kJ versus 6500 kJ). The two diverse training protocols induced remarkably similar adaptations in exercise performance and skeletal muscle oxidative capacity, as reflected by the maximal activity of cytochrome c oxidase (Figure 1). To our knowledge this was the first study to demonstrate that HIT is indeed a very 'time-efficient' strategy to induce adaptations normally associated with endurance training.

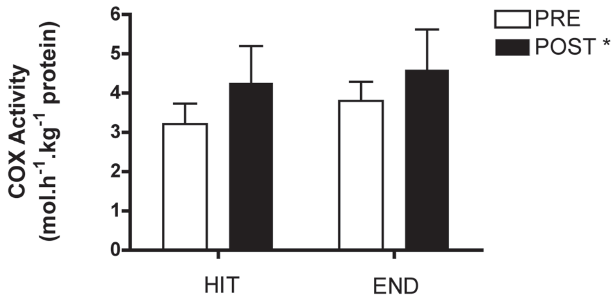

FIGURE 1. Maximal activity of cytochrome c oxidase measured in resting human skeletal muscle biopsy samples obtained before (PRE) and after (POST) six sessions of high-intensity interval training (HIT) or continuous moderate-intensity training (END) lasting two weeks. Total training time commitment was approximately 2.5 h and 10.5 h for the sprint and endurance groups, respectively, and total exercise volume was approximately 90% lower for the HIT group. Values are means ± SE for 8 subjects in each group. *P<0.05 versus PRE (main effect for time). [Reprinted with minor modifications from Gibala et al. (2006) with permission.]

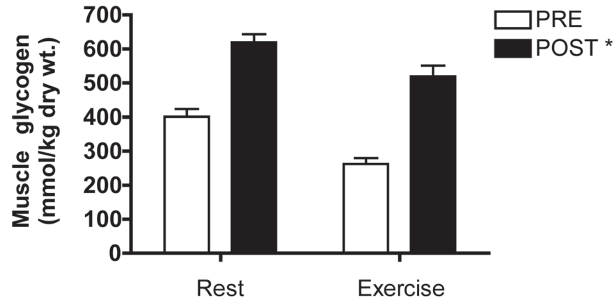

FIGURE 2. Glycogen content measured in human skeletal muscle biopsies obtained at rest and after 20 min of matched-work exercise, before (Pre) and after (Post) two weeks of high-intensity interval training. Exercise consisted of 10 min at 60% VO_2peak followed by 10 min at 90% VO_2peak at the same absolute workload before and after training. Values are means ± SE, n=8. *Main effect for trial (Posttraining > pretraining, P<0.05). Net muscle glycogenolysis during the exercise bout was also lower posttraining vs. pretraining (P<0.05). [Reprinted with minor modifications from Burgomaster et al. (2006) with permission.]

In addition to an increased skeletal muscle oxidative capacity after two weeks of HIT, we have also detected changes in carbohydrate metabolism that are normally associated with traditional endurance training, including an increased resting glycogen content and reduced rate of glycogen utilization during matched-work exercise (Figure 2) and increased total GLUT-4 protein content in muscle (Burgomaster et al, 2006; 2007). But after our short-term Wingate-based training intervention we found no changes in selected markers of fatty acid metabolism, including the maximal activity of ß-hydroxyacyl-CoA dehydrogenase (HAD) and the muscle contents of fatty acid translocase (FAT/CD36) or (FABPpm), a fatty-acid-binding protein associated with the plasma membranes (Burgomaster et al., 2006; 2007). In contrast, Talanian and coworkers (2007) recently reported that seven sessions of HIT over two weeks increased the maximal activity of HAD, the muscle protein content of FABPpm, and whole-body fat oxidation during 60 min of cycling at 65% pre-training VO_2peak. A major difference between our recent studies (Burgomaster et al., 2006; 2007; Gibala et al., 2006) and the work of Talanian et al. (2007) was the nature of the HIT stimulus. Subjects did not perform "all out" sprints in the latter study; however, each training session consisted of ten 4-min bouts of cycling at 90% of VO_2peak with 2 min of rest between intervals. Total training time commitment (~5 h) and exercise volume (~3000 kJ) over the two-week training period was thus substantially higher than in our recent studies that have employed Wingate-based exercise training (Burgomaster et al., 2006; 2007).

How Does HIT Stimulate Adaptations in Skeletal Muscle?

The potency of HIT to elicit rapid changes in skeletal muscle is doubtless related to its high level of muscle fiber recruitment and potential to stress type-II fibers in particular (Gollnick & Saltin, 1983), but the underlying mechanisms are unclear. When trying to determine what molecular signals develop that lead to adaptations in muscle, exercise is typically classified as either "strength" or "endurance," with short-duration, high-intensity work usually associated with increased skeletal muscle mass, and prolonged, low-to-moderate-intensity work associated with increased mitochondrial mass and oxidative enzyme activity (Baar, 2006). Indeed, the distinct intracellular signaling pathways that regulate either cell growth or mitochondrial production intersect at a number of points in an inhibitory fashion, resulting in a response that is largely exclusive for one type of exercise or the other (Baar, 2006).

Relatively little is known regarding the intracellular signaling events that mediate skeletal muscle remodeling in response to HIT, which, unlike traditional strength training, is not characterized by marked skeletal muscle hypertrophy (Ross & Leveritt, 2001). Rather, given the rapid changes in mitochondrial oxidative capacity that result from HIT, it seems likely that metabolic adaptations to this type of exercise could be mediated in part through signaling pathways normally associated with endurance training. Contraction-induced metabolic disturbances activate several enzyme systems that participate in signaling pathways shown to play a role in promoting specific molecular activators involved in mitochondrial production and metabolism (Hawley et al., 2006). Additional research is warranted to clarify the effect of different acute exercise 'impulses' on molecular signaling events in human skeletal muscle and the precise time course and mechanisms responsible for adaptations induced by HIT.

Short-term HIT Rapidly Improves Exercise Capacity

From a practical perspective, one of the most striking findings from our recent studies was the dramatic improvement in exercise performance during tasks that rely mainly on aerobic energy metabolism, despite the very low training volume (Burgomaster et al., 2005; 2006; 2007; Gibala et al., 2006). In our initial study (Burgomaster et al., 2005), subjects doubled the length of time that exercise could be maintained at a fixed submaximal workload — from ~26 min to 51 min during cycling at 80% of pre-training VO_2peak —after only six HIT sessions (Figure 3). The validity of this finding was bolstered by the fact that a control group showed no change in performance when tested two weeks apart with no training intervention. Subsequent work confirmed that two weeks of HIT improved performance during tasks that more closely resemble normal athletic competition, including laboratory time trials that simulated cycling races lasting from ~2 min to ~1 h (Burgomaster et al., 2006; 2007; Gibala et al., 2006).

Obviously, the factors responsible for training-induced improvements in exercise capacity are complex and are determined by numerous physiological (e.g., cardiovascular, ionic, metabolic, neural, respiratory) and psychological attributes (e.g., mood, motivation, perception of effort). We have found no measurable change in VO_2peak after two weeks of Wingate-based HIT (Burgomaster et al., 2005; 2006; 2007; Gibala et al., 2006), which suggests the improved exercise performance was related in part to peripheral adaptations in skeletal muscle as described above. Other investigators have reported an increased VO_2peak after as little as two weeks of HIT (Rodas et al., 2001; Talanian et al., 2007), but the total work performed in those studies was considerably greater than in our investigations.

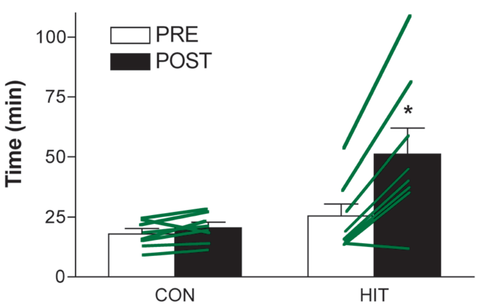

FIGURE 3. Cycle time to exhaustion at 80% of pre-training VO_2peak before (PRE) and after (POST) six sessions of high-intensity interval training (HIT) lasting two weeks or an equivalent period without training (control; CON). Individual (green lines) and mean ($\bar{X}$±SE) data are plotted for 8 subjects in each group. *P<0.05 versus PRE within same condition. [Reprinted with minor modifications from Burgomaster et al. (2005) with permission.]

Implications: How Much Exercise is Enough?

Although there is consensus regarding the importance of physical activity, the minimum dose necessary to improve health status is unclear (Blair et al., 2004). Public health guidelines generally recommend 30-60 min of moderate-intensity exercise on most days of the week. However, despite overwhelming scientific evidence that regular physical activity is effective in the prevention of chronic diseases and premature death, most adults fail to meet even the minimum physical activity guidelines. Countless studies have shown that the most commonly cited reason for not exercising is a “lack of time” (Godin et al., 1994). This finding is universal; regardless of age, ethnicity, sex, or health status, people report that a lack of time is the primary reason for their failure to exercise on a regular basis. Given that lack of time is such a common barrier to exercise participation, innovations in exercise prescription that yield benefits with minimal time commitments represent a potentially valuable approach to increasing population activity levels and population health. HIT is often dismissed outright as unsafe, unpractical or intolerable for many individuals. However, there is growing appreciation of the potential for intense, interval-based training to stimulate improvements in health and fitness in a range of populations, including persons with various disease conditions (Rognmo et al., 2004; Warburton et al., 2005). In addition, some data suggests that a low-frequency, high-intensity approach to training is associated with greater long-term adherence as compared to a high-frequency, low-intensity program (King et al., 1995).

Limitations and Perspective

Our recent studies should not be interpreted to suggest that low-volume interval training provides all of the benefits normally associated with traditional endurance training. The duration of the training programs in our published work to date was relatively short (six sessions over two weeks), and it remains to be determined whether similar adaptations are manifest after many months of low-volume interval and high-volume continuous training. It is possible that the time course for physiological adjustments differs between training protocols; the very intense nature of interval training may stimulate rapid changes, whereas the adaptations induced by traditional endurance training may occur more slowly. Second, the Wingate-based training model that we have employed requires a specialized ergometer and an extremely high level of subject motivation. Given the extreme nature of the exercise, it is doubtful that the general population could safely or practically adopt the model. Like the recent work by Talanian et al. (2007), future studies should examine “modified” interval-based approaches to identify the optimal combination of training intensity and volume necessary to induce adaptations in a practical, time-efficient manner. Finally, to date we have only examined a few specific variables in skeletal muscle; future studies should examine whether low-volume interval training induces other physiological adaptations normally associated with high-volume endurance training, including changes in health-related outcome markers such as insulin sensitivity.

SUMMARY

Elite endurance athletes have long appreciated the role for HIT as part of a comprehensive training program. Recent evidence shows that — in young healthy persons of average fitness — intense interval exercise is a time-efficient strategy to stimulate skeletal muscle adaptations comparable to those achieved by traditional endurance training. As little as six sessions of HIT over two weeks, or a total of only ~15 min of very intense exercise, can increase skeletal muscle oxidative capacity and improve performance during tasks that rely mainly on aerobic energy metabolism. However, fundamental questions remain regarding the minimum volume of exercise necessary to improve physiological well being in various populations, the effectiveness of alternative (less extreme) interval-training strategies, and the precise nature and magnitude of adaptations that can be elicited and maintained over the long term.

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SUPPLEMENT

WHAT CAN HIGH-INTENSITY INTERVAL TRAINING DO FOR YOU?

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INTERVAL TRAINING generally refers to repeated sessions of relatively brief, intermittent exercise, in which short intervals of intense exercise are separated by longer periods of recovery. Depending on the level of exertion, a single effort may last from a few seconds to several minutes, with exercise intervals separated by up to a few minutes of rest or low-intensity exercise.

High-intensity interval training is often dismissed as being only for elite athletes. However, the basic concept of alternating high-intensity and low-intensity periods of exercise can be applied to almost any level of initial fitness. In addition, interval training is often based on subjective effort and does not necessitate working out at a specific heart rate or running speed. So while intervals may mean all-out running sprints for people with high levels of fitness, intervals can mean a brisk walk for others.

Benefits

- High-intensity intervals are a potent training stimulus. Even though the volume of exercise is quite small, a few brief sessions of intervals can cause adaptations similar to those associated with more prolonged periods of continuous moderate-intensity exercise.
- You only need to do intervals every other day, so you have more days off. This is great news for people who are pressed for time.
- Time flies. Not only will you be able to reduce your training time, but also the actual exercise component will zip by because of the alternating periods of intensity.

Limitations

- Discomfort. Intervals are very strenuous, and your legs will feel like jelly at the end of the workout. While you don't have to exercise at 100% intensity to see results, you will have to leave your "workout comfort zone" if you want to achieve the benefits of high-intensity training.
- You will need to do an extended warm-up session if you plan on running sprints for your interval training sessions. Explosive running may increase your risk of injury compared to less weight-bearing activities such as cycling or swimming. If you run your intervals, try doing them up a hill.
- Be sure to dramatically reduce exercise intensity during the recovery periods between intervals. Most people do interval training incorrectly and do not permit themselves sufficient recovery. If you don't recover adequately, you are not going to be able to work as hard during the exercise intervals.
- Before returning to strenuous training or competition after injuries, consult with an athletic trainer, personal trainer, sports medicine physician, or knowledgeable coach to make certain you have adequate strength in the previously injured limb(s).

The science behind interval training also helps to bury myths such as the "fat burning zone" and "it takes 30 minutes of exercise before your body begins to burn fat." Skeptics often dismiss the fat loss potential of high-intensity exercise because the intervals are relatively short. But energy expenditure remains high during the recovery periods between exercise intervals, even though exercise intensity is dramatically reduced. To demonstrate this point, a recent study showed that only seven sessions of high-intensity interval training over two weeks increased fat burning during exercise by more than 30%.

As with any type of unaccustomed exercise, you should consult with your physician before beginning interval training. But high-intensity exercise in not "a heart attack waiting to happen." Indeed, recent studies have applied high-intensity interval training strategies to patients with heart disease and reported greater improvement in health and fitness compared to traditional endurance training.

Sample Workouts

Here's a sample program for an absolute beginner (someone who can walk for 30 min at 3.5 mph):

- Warm up: Five minutes of walking at 3.5 mph.
- Speed up and walk at 4.0 mph for 60 seconds.
- Slow down and stroll at 3.0 mph for 75 seconds.
- Repeat steps 2 and 3 five more times.
- Finish with 5 minutes of walking at a comfortable pace to cool down.

Here's an example of a more advanced workout for a person who is used to relatively vigorous exercise:

- Warm up: Five minutes of easy jogging or light cycling.
- Run or cycle for 60 seconds at about 80-90% of your all-out effort. (Assume 100% equals the speed you would run to save your life, or cycle with as high a cadence as possible at the highest possible workload setting).
- Slow down to 30% of your all-out effort for 75 seconds. (Make sure to reduce intensity to a slow pace.)
- Repeat steps 2 and 3 five more times.
- Finish with 5 minutes at 30% of your all-out effort to cool down.

As you become more experienced, you can increase the intensity of the exercise intervals. You can also use different modes of exercise to do intervals. If you like to train outdoors, you can perform hill sprints or run in waist-deep water. If you are resigned to training at a commercial gym, you can choose between the treadmill, cross-trainer, stationary bike, and even the rowing machine. It all comes down to having the ability to increase the workload for a short amount of time and then being able to back off.

COMMENT

It is unlikely that high-intensity interval training produces all of the benefits normally associated with traditional endurance training. The best approach to fitness is a varied strategy that incorporates strength, endurance and speed sessions as well as flexibility exercises and proper nutrition. But for people who are pressed for time, high-intensity intervals are an extremely efficient way to train. Even if you have the time, adding an interval session to your current program will likely provide new and different adaptations. The bottom line is that — provided you are able and willing (physically and mentally) to put up with the discomfort of high-intensity interval training — you can likely get away with a lower training volume and less total exercise time.

SUGGESTED ADDITIONAL RESOURCES

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