Muscle glycogenolysis and resynthesis in response to a half Ironman triathlon: A case study

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MUSCLE GLYCOGENOLYSIS AND RESYNTHESIS IN RESPONSE TO A
HALF IRONMAN TRIATHLON: A CASE STUDY

By

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B.Sc. University of Oklahoma, 2004

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Approved by:

Chairperson

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Muscle Glycogenolysis and Resynthesis in Response to a Half-Ironman Triathlon: A Case Study

Chairperson: Brent C. Ruby

The purpose of the study was to describe the degrees of muscle glycogen depletion and resynthesis in response to a half Ironman triathlon.

One male subject (38 yr.) completed the Grand Columbian half Ironman triathlon (1.9 km swim, 90 km bike, 13.1 km run). Three muscle biopsies were obtained from the subject’s right vastus lateralis (pre-race, immediately post-race, and four hours post-race). Pre and post-race body weight was recorded, in addition to macronutrient consumption before, during, and after the race. Energy expenditure and whole body substrate oxidation was estimated from linear regression established from laboratory trials (watts and run pace relative to VO2 and VCO2).

Overall finish time for the race was 4:48:53 (33:33 swim, 2:43:11 bike, 1:28:40 run). Body weight decreased 3.8 kg from pre to post-race. Estimated CHO energy expenditure (EE) for the bike segment was 10,003 KJ (641g CHO, 88% of cycle EE) and 5,759 KJ (369g CHO, 86% of total run EE) for the run segment of the race. A total of 308g CHO (liquid and gel) was consumed (1.21 g CHO/min). Muscle glycogen decreased from 227.1 pre-race to 38.6 mmol kg wet wt. post-race. During the four hours post-race, a mixed diet was consumed (471g CHO, 15g Fat, 64g Protein) which included scheduled liquid CHO sources (Gatorade energy drink) and a meal. The calculated rate of muscle glycogen resynthesis was 4.1mmol·kg·hr⁻¹·wt·wt.

The completion of a half Ironman triathlon is dependent on a high rate of muscle glycogenolysis, which demonstrates the importance of exogenous carbohydrate intake during the race. In addition, rates of muscle glycogen resynthesis may be dampened by the eccentric damage resulting from the run portion of the race.

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Introduction

Triathlon is a distinct sporting event combining three disciplines (swimming, cycling, and running) that impose unique metabolic and nutritional concerns for the working muscle depending on the duration of the event. The half Ironman triathlon consists of a 1.9km swim, followed by a 90km cycle, and 21.1km run.

Limited research has been conducted during a triathlon in regards to the intensity of the race. Roalstad et al. examined heart rate monitoring in ultraendurance events concluding that subjects completed the cycling portion of the Hawaii Ironman triathlon at an intensity of ~75% of maximum heart rate (HR\text{max})\textsuperscript{41}, which corresponds with O’Toole’s suggestion that highly trained triathletes may be expected to average 80% of their peak heart rate (HR) during an ultra endurance triathlon\textsuperscript{36}. Laursen et al. concluded that performance HR in elite endurance athletes during both the cycle and run portions of a full Ironman triathlon was closely correlated to the first ventilatory threshold HR (HR\text{vent}) measured during previous progressive exercise tests\textsuperscript{34}.

Fatigue during prolonged, intense exercise is believed by many researchers to be associated with glycogen depletion in working skeletal muscles\textsuperscript{16}. Although endogenous glycogen stores are limited, pre race diet can increase these stores, proper training can temper their utilization, and in race feeding can attenuate their decline. Muscle glycogen and blood glucose are the most important substrates for contracting muscle\textsuperscript{5}. Muscle glycogen depletion, and reduced blood glucose concentrations are associated with fatigue during prolonged exercise\textsuperscript{9}. To retard fatigue and perform optimally it is advantageous to obtain high pre-exercise muscle and liver glycogen concentrations, as well as maintain adequate nutrition during the contest.
Muscle glycogen is a vital fuel source for moderate to high intensity exercise. Once exhausted, the capacity to perform at these exercise intensities is lost or severely restricted. Following exhaustion, the more rapidly the muscle glycogen can be restored after exercise, the quicker the recovery process and theoretically the more effective the return to performance capacity. In recent years, research has focused on the timing, frequency, amount, and type of ingested post-exercise supplementation to effectively replenish glycogen stores.

Although previous studies have shown the metabolic response of muscle glycogenolysis and resynthesis to ultra endurance exercise in the lab, it remains to be elucidated if these same responses will manifest themselves in the same degree during an actual race. Despite considerable research examining laboratory based responses of substrate utilization and glycogen depletion of >4 hours of contractile activity, relatively little information is available concerning responses during a triathlon.

Due to the limited amount of fieldwork relating to calculated rates of muscle glycogenolysis, particularly in the sport of triathlon, the purpose of this study was to describe the degrees of muscle glycogen depletion and resynthesis in response to a half Ironman triathlon.
Review of Literature

Introduction

Ultra-endurance exercise is classified as prolonged exercise lasting longer than 4 hours\(^4\). The half Ironman triathlon is the epitome of ultra-endurance exercise commonly requiring 4-10 hours to complete the event. In any ultra-endurance endeavor, nutrition becomes a vital factor to a racer’s success. Fatigue during prolonged, intense exercise is associated with glycogen depletion in working skeletal muscles\(^2\). Muscle glycogen content is closely related to endurance capacity. Although endogenous glycogen stores are limited, pre race diet can increase these stores, proper training can temper their utilization, and in race feeding can attenuate their decline. The theory behind the ingestion of increased carbohydrates (CHO), both in the days leading up to the event and while participating, is to increase the storage of glycogen, thereby preventing hypoglycemia from depleted liver glycogen and storing increased muscle glycogen as a functional fuel source for the working muscles, perhaps delaying the onset of fatigue\(^4\).

In this literature review I will discuss the need for both CHO and fluid before, during, and after exercise, and the utilization of CHO both during exercise and post exercise for muscle glycogen resynthesis.

Supercompensation Prior to Exercise

The importance of muscle glycogen as a metabolic substrate in sustaining prolonged exercise has been well documented. Due to the close proximity to the site of contraction, and the ability to sustain high rates of adenosine diphosphate (ADP) phosphorylation, glycogen is viewed as the principal fuel for the continuance of exercise of a moderate to intense nature. To assure optimal exercise performance, endurance
athletes are encouraged to maximize the availability of muscle glycogen through training
and the ingestion of a high carbohydrate (CHO) diet prior to competition. Current recommendations by Hawley et al. suggest that supercompensating muscle glycogen levels preceding exercise can improve performance by 2-3% in events lasting longer than 90 minutes. It was previously advocated to supercompensate glycogen levels only after a glycogen depleting exercise, followed by 3 days of a diet rich in fat/protein, and low in carbohydrates. Researchers have found this arduous protocol may increase muscle glycogen stores by more than twice the normal glycogen concentration. Of greater importance was the finding that pre-exercise muscle glycogen concentration was directly related to endurance capacity. As science evolved, new research by Sherman et al. revealed that glycogen stores could be supercompensated by less radical exercise and dietary maneuvers. Sherman et al. demonstrated that 3 days of moderate CHO consumption, 50% of energy intake coming from CHO, followed by 3 days of high CHO intake, 70% coming from CHO in conjunction with a tapered training program lead to supercompensated muscle glycogen concentrations. Numerous researchers have recently publicized that the consumption of a high CHO diet without a glycogen depleting exercise bout lead to supercompensated muscle glycogen concentrations. Researchers have suggested that 12.5 g of CHO/kg BW/day during 6 consecutive days of training without tapering lead to elevated glycogen levels. Bussau et al. has more recently shown that glycogen supercompensation could be attained with only a 1 day, high CHO (10.5g of CHO/kg BW/day) ingestion and complete physical inactivity.
In summary, there is conclusive evidence showing that high muscle glycogen concentrations improve performance (i.e. time to complete a predetermined distance) and endurance capacity (time to fatigue) in events lasting longer than 90 minutes. To attain high muscle glycogen concentrations, ultra-endurance athletes should consume a CHO rich diet, 10g of CHO/kg BW/day, at least 24 hours prior to the event.

**High CHO Pre Exercise Meal**

The importance of a high CHO pre-exercise meal has been well documented\(^\text{38, 44}\). Sherman et al. found that the intake of at least 200g of CHO in the 4 hours preceding exercise not only increased endurance, but improved performance during a time trial after a prolonged bout of cycling. Pre-exercise meals may enhance CHO availability during exercise by increasing muscle and liver glycogen stores, or by providing a source of glucose in the gut for later release. Pre-exercise CHO load may be of particular importance for races that begin in the morning after an overnight fast, when glycogen stores are substantially depleted\(^\text{44}\).

Although it is clear that increased CHO consumption in the days leading up to the race, as well as 3-4 hours prior to the start of the race, can have a positive impact on performance there is debate as to whether ingestion of CHO 30-60 minutes prior to the start of the race is advantageous. The effects most associated with this late pre-race feeding strategy are hypothesized to be the elevation of plasma insulin concentrations acting to suppress fat metabolism, accelerate CHO oxidation, and cause a decline in plasma glucose concentration as exercise starts\(^4\). Exercise, in addition to high insulin as a result of pre-race CHO ingestion, causes a rapid decline in blood glucose within 15-30 min of the start of exercise. This has been termed rebound hypoglycemia and has been
the topic of numerous studies. However, numerous researchers have concluded that rebound hypoglycemia in the early stages of exercise does not affect exercise performance and seems to be of little 'functional' significance, suggesting that there is no need to avoid CHO intake 30-60 minutes prior to exercise.\textsuperscript{25,46}

In summary, the ingestion of a high CHO pre-race meal may improve performance by enhancing CHO availability by increasing muscle and liver glycogen stores, or by providing a source of glucose in the gut for later release. Recent research suggests that there is no need to avoid CHO 30-60 min prior to the start of the race.

**CHO Supplementation During Exercise**

CHO supplementation during prolonged exercise is vital for sustaining plasma glucose levels, thus sparing the conversion of liver glycogen to plasma glucose and maintaining adequate rates of glucose oxidation during lower, prolonged exercise intensity (55\% \textit{VO}_{2peak}). However, consuming CHO has not been shown to slow the rate of glycogen utilization by working muscles.\textsuperscript{9} Kang et al. concluded that CHO ingestion during prolonged exercise, along with CHO supercompensation prior to the event lead to enhanced endurance performance. Furthermore, Kang hypothesized that this superior performance was due to the maintenance of plasma glucose concentrations and a greater availability of exogenous CHO energy substrates during the later stages of the race.\textsuperscript{31} In one of the only studies to examine energy balance during an actual Ironman triathlon, Kember et al. found that overall CHO intake during the triathlon was inversely correlated with finishing time in males, and correspondingly, found an inverse relationship between relative CHO intake during the run and finishing time in males. Thus, increasing CHO intake during the run portion was related to improved performance, and could be a useful
strategy for preventing fatigue associated with glycogen depletion. In this study, male triathletes consumed an average of 1.1 g/kg BW/hour throughout the event. To reach these high levels of CHO ingestion, athletes consumed 3 times the amount of CHO during cycling compared to the running portion\textsuperscript{33}.

When fed a glucose polymer during cycling (2.0 g/kg at 20 min and 0.4 g/kg every 20 min thereafter) plasma glucose concentrations were maintained and endurance trained cyclist were able to sustain exercise at \(\sim 71\%\) of \(\text{VO}_2\text{max}\) for an additional hour (placebo group 3.02 +/- 0.19 hr, experimental group 4.02 +/- 0.33 hr) compared to the placebo fed control group. The CHO fed group maintained their ratio of CHO: fat and absolute rate of carbohydrate oxidation throughout exercise. Interestingly, the pattern of muscle glycogen depletion was not different for the first 3 hours of exercise with the placebo or the carbohydrate feedings. The additional hour of exercise performed when fed carbohydrate was accomplished with little reliance on muscle glycogen and without compromising carbohydrate oxidation\textsuperscript{9}.

According to Jeukendrup et al., exogenous CHO oxidation rates do not exceed 1.0-1.1 g/min, therefore, it has been recommended to ingest 60-70 g/hour of CHO during prolonged exercise\textsuperscript{27}. However, studies have demonstrated that not all CHO are oxidized at similar rates. Jentjens et al. proclaimed that a CHO mixture of glucose and sucrose, or glucose and fructose, when ingested at high rates (1.8 g/min), lead to peak oxidation rates of 1.2-1.3 g/min and resulted in 20-50% higher exogenous CHO oxidation rates compared with the ingestion of isocaloric glucose\textsuperscript{26}. Jentjens hypothesized that these CHO\textsubscript{s} are absorbed by different intestinal transport mechanisms. While a faster rate of intestinal absorption leads to an increase in the availability of exogenous CHO in the
blood stream for oxidation, it still remains to be seen if these findings will lead to increased endurance performance.

In summary, CHO supplementation during an ultra-endurance event is important to sustain plasma glucose levels, thus sparing the conversion of liver glycogen to plasma glucose. To achieve peak CHO oxidation rates, it appears a mixture of glucose and sucrose, or glucose and fructose should be consumed at a rate of 1.8 g/min throughout the event. Maximum rates of CHO oxidation approach 1.3 g/min. Data from past field studies suggest that the cycle portion is the most advantageous leg of the triathlon during which to consume high rates of CHO

**Fluid Balance**

There are many problems associated with fluid imbalance in ultra-endurance sport. If insufficient fluids are ingested, and fluid deficit occurs, plasma and stroke volume decline. With dehydration, heart rate increases, cardiac output decreases as critical values are recorded, and core body temperature increases. However, with adequate hydration and fluid balance, these responses are attenuated. In contrast, if the volume of fluid ingested is too high, hyponatremia may ensue, a potentially life threatening condition.

The current ACSM stand on fluid intake during exercise suggests fluid consumption of 600-1200 ml/h containing 6-8% CHO and 0.5-0.7 g/l of sodium for events lasting longer than 1 hour. However, recent research has questioned the recommendations made by the ACSM. The volume is considered too high for most ultra-endurance athletes competing at relatively low intensities or for smaller athletes with relatively low metabolic and sweat rates during exercise. Female ultra-endurance
athletes, because of their lower sweat rates, smaller fluid compartments, and the longer time taken to complete the event compared to males, may have lower fluid requirements and are at significantly greater risk of developing hyponatremia due to fluid overload.48

In lieu the ACSM guidelines, ultra-endurance athletes are advised to take a more modest approach to fluid consumption. In ultra-endurance competition, it is recommended to limit fluid intake to 500-800 ml/hr during the cycle and 200-500 ml/hr during the run, with lightweight men and women being advised to drink lower volumes.38 A 5-10% CHO concentration appears not to affect gastric emptying, making it possible to combine fluid ingestion and CHO requirements during exercise.4

In one of the only studies to examine fluid balance during an Ironman triathlon, Speedy et al. reported an hourly fluid intake of 716 ml/hr (range 421-970 ml/hr) during the 1996 New Zealand Ironman triathlon. Fluid consumption was highest on the cycling portion of the race with an average intake 889 ml/hr. During the race, athletes lost an average of 2.5 kg. Fluid intakes during this event were more modest than the ACSM recommendations.47

In summary, the ACSM recommendations for fluid intake for activities lasting longer than 1 hour may be somewhat aggressive. According to the most recent research, 500-800 ml/hr during the cycling stage, and 300-500 ml/hr during the running leg of fluid containing 5-10% CHO, adjusted for body size and temperature, is advantageous for ultra-endurance exercise.

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CHO and Fat Utilization

CHO and fats are the most important fuels at rest and during exercise. The rate of CHO oxidation during extended exercise is closely linked to the energy demands of the active muscle and training status of the individual. Conversely, the oxidation of fat during prolonged exercise is not strictly controlled, for there are no means for closely matching the availability and metabolism of fatty acids to the rate of energy expenditure. As a result, the rate of fat oxidation during exercise is established by the rate of CHO utilization and by the availability of fatty acids.³⁸

CHO is stored as glycogen in the muscle and liver. Typically, the liver holds 80-100 g of glycogen in the post absorptive state, whereas muscle glycogen can fluctuate between 20 mmol kg⁻¹ wet wt. of muscle after arduous exercise to 300 mmol kg⁻¹ wet wt. of muscle in a well-fed, well-trained person. At rest and during exercise, substrates are mobilized from these stores and employed within the skeletal muscle.³⁹

Fat stores, primarily in adipose tissue, are large compared to glycogen representing 92-98% of all endogenously stored energy. In addition to adipose fat, considerable amounts (~300g) can be found in skeletal muscle in the form of intramuscular triacylglycerol (IMTAG). Both during activity and rest, fat stores are used as a necessary substrate.³⁹

Generally, the oxidation of CHO and fat occurs simultaneously, but the relative contribution of each substrate depends on many factors. These factors include exercise intensity, duration, diet, environmental conditions, gender, and training status.³⁹

At the onset of exercise, liver glycogen breakdown will increase as the hepatic glucose output increases as a function of exercise intensity. Exercise rapidly stimulates
glucose transport activity in the plasma membrane of the active muscle, resulting in an increase in the influx of glucose into the cytosol. This transport of glucose through the sarcolemma is the primary rate limiting step for blood glucose metabolism in striated muscle. Glucose is transferred into the cell by two primary glucose transport proteins; GLUT1 and GLUT4. The less abundant GLUT1 isoform is thought to reside primarily in the sarcolemma and contribute to basal glucose transport. The GLUT4 isoform is the major glucose transporter in skeletal muscle. As exercise intensity increases there is increase reliance on muscle glycogen over transported blood glucose. Above ~50% VO2max, there is a shift in muscle glycogen utilization when exercise intensity is increased\textsuperscript{18}.

In summary, CHO and fats are the most important fuels at rest and during exercise. When exercise starts, the rate of lipolysis and glycolysis is increased as the exercise intensity is increased. Research suggests that at ~ 65% VO2max, there is an increased reliance on CHO oxidation, and fat oxidation is reduced.

**Role of Duration**

The duration of exercise affects substrate oxidation. Research suggests that fat oxidation increases and CHO oxidation decreases as exercise continues. The increase in fat oxidation is typically due to the reduction of glycogen and IMTG stores and a progressive rise in plasma FA concentrations toward the latter stages of exercise\textsuperscript{18, 28}.

**Role of Intensity**

Brooks has highlighted the significance of exercise intensity relative to VO2max in calculating the involvement of CHO and fat oxidation to total energy utilization. He has
created the term "crossover point" for the relative exercise intensity at which the predominant fuel for oxidative metabolism shifts from fat to CHO. This crossover point, which usually occurs ~50% VO\textsubscript{2max} in mildly trained or untrained individuals who have been eating a usual, mixed diet, is a useful reference point for evaluating the effects of various physiological and metabolic states, and adaptations such as diet and training on the fuel mixture used during exercise\textsuperscript{3}.

**Role of Diet**

The single largest influence that can alter the crossover point is diet. Researchers found that cycling at 65% of VO\textsubscript{2max} elicited a respiratory exchange ratio (RER) of 0.92 in subjects on a high CHO diet, compared to an RER of 0.81 in the same subjects after they had been eating a high fat diet for seven days. An RER of 0.81 indicates that CHO oxidation is providing 34% of the total energy, thus these subjects were still well below the crossover point when exercising at 65% VO\textsubscript{2max} on a high fat diet\textsuperscript{22}.

Fat oxidation rates were elevated 72%, and whole body lipolysis 79% after a two day diet consisting of 60% fat, compared to the isocaloric control group consuming 22% fat, in endurance trained cyclist exercising at 50% VO\textsubscript{2peak} for one hour. Consequently, CHO oxidation decreased by 38% below the control group during the one hour exercise bout. Although acipimox, an adipose lipolysis inhibitor ingested before exercise in both groups, lowered plasma free fatty acid (FFA) availability, the high fat diet group still increased fat oxidation above the control to the same extent as the increase caused by the high fat diet without acipimox. These findings lead the authors to conclude that the higher fat oxidation during exercise after a short term, high fat diet is associated with
elevated IMTG concentrations and whole body lipolysis. However, this does not appear to depend on elevated adipose lipolysis and plasma FFA concentrations because adipose tissue lipolysis inhibition with acipimox did not attenuate the absolute increase in fat oxidation and lipolysis. This finding suggests that the major substrate responsible for elevated fat oxidation and lipolysis after a short term, high fat diet is IMTG°.

In a similar study, RER was measured before, after two weeks, and after 4 weeks of a isocaloric high fat diet (consumed 95% more fat and 52% less CHO compared with the habitual diets) compared to a high CHO group (14% less fat, 39% more CHO compared with the habitual diets). After week two and week four, the RER for the high fat diet group during exercise at 80% VO2max was significantly lower compared with RER values during exercise after the CHO rich diet. After two and four weeks on the CHO rich diet, RER values were unchanged15.

In summary, the single largest influence that can alter the crossover point is diet. It has been shown that a consistent diet rich in fat can lead to higher rates of fat oxidation with diminished reliance on CHO as a fuel during exercise.

**Role of Training**

The intensity at the crossover point, where CHO and fat oxidation are balanced, can be raised by adaptation to endurance training. In a study in which 8 men underwent 12 weeks of endurance training that raised their VO2max 26%, the RER during the final 10 minutes of exercise that elicited 60% of their pre trained VO2max was 0.93 (76% of energy from CHO) before training, and 0.89 (62% of energy from CHO) after training. A group of highly trained endurance athletes were studied at the same time. At an exercise
intensity that required 80% VO$_{2\text{max}}$, the athletes RER was 0.89 (62% of energy from CHO; the same as post trained values of the subjects exercising at only 60% VO$_{2\text{max}}$) compared to an RER of 0.96 (86% of energy from CHO) in untrained subjects$^{20}$.  

In a similar study, the rates of glucose appearance and disappearance were measured in highly trained and untrained subjects. Researchers concluded that trained subjects obtained more of their energy from fat and less from CHO oxidation during exercise requiring 80% VO$_{2\text{max}}$ than did untrained subjects$^6$.  

In summary, many factors affect substrate utilization. Research data supports that the longer the exercise session lasts without exogenous CHO fuels, the greater the reliance placed on fat oxidation. The crossover point, at which the predominant fuel for oxidative metabolism shifts from fat to CHO, is around 50% VO$_{2\text{max}}$ in untrained or moderately trained individuals. A large influence that can alter the crossover point is diet. It has been shown that a consistent diet rich in fat can lead to higher rates of fat oxidation with diminished reliance on CHO as a fuel during exercise. Highly endurance trained athletes show signs of sparing glycogen stores placing a greater dependence on fat oxidation during exercise at relative and absolute intensities.

**Post Exercise Muscle Glycogen Synthesis**

Muscle glycogen is a vital fuel source for moderate to high intensity exercise. Once exhausted, the capacity to perform at these exercise intensities is lost or severely restricted. Therefore, the more rapidly the muscle glycogen can be restored after exercise, the quicker the recovery process and theoretically the more effective the return to performance capacity$^{21}$. 

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In recent years, research has focused on the timing, frequency, amount, and type of ingested post-exercise supplementation to effectively replenish glycogen stores. Ivy et al. has been a leader in these investigations. His research has shown that the ingestion of a 378 kcal CHO bolus supplemented with protein (Pro) (80 g CHO, 28 g Pro) immediately following exercise, and two hours post, was more effective at restoring glycogen in the 4 hours directly following exercise than either an isocaloric low CHO (80 g CHO, 6 g fat) or high CHO (108 g CHO, 6 g fat) intake. In the CHO-Pro treatment, the difference in total glycogen storage was a result of a greater rate of glycogen storage during the first 40 minutes of recovery and a more sustained rate of glycogen storage during the final two hours of recovery. From this study, it appears that the mechanism by which CHO-Pro supplementation increases the rate of muscle glycogen storage is unrelated to an enhanced plasma insulin response as previously thought, but rather related to lower plasma glucose and lactate concentrations, as seen during the CHO-Pro trial. This observation may indicate an increase in plasma glucose uptake and a redistribution of intracellular glucose disposal by the addition of protein to a CHO supplement21.

However, whether the advantage of CHO-Pro supplement relative to muscle glycogen storage is maintained when compared with a high frequency of CHO intake remains to be elucidated. Large, frequent (every 15-30 min) doses of CHO have been shown to facilitate glycogen storage rates significantly higher than those seen when supplementing every two hours27, thus altering the rate of CHO absorption and limiting the effects of Pro supplementation. Jentjens et al. concluded that when CHO supplementation is increased to 1.2 g·kg⁻¹·hr⁻¹, and provided every 30 min, the addition of protein supplementation does not further increase the rate of muscle glycogen storage23.
It has been demonstrated that higher muscle glycogen content is associated with decreased muscle glucose uptake\textsuperscript{11, 17, 40}. Therefore, it is possible that the rate of muscle glycogen resynthesis is greater in humans four hours post exercise with delayed CHO ingestion compared with immediate feedings\textsuperscript{37}. Parkin et al. found that delaying the ingestion of high glycemic index foods by two hours has no effect on muscle glycogen storage at eight and 24 hours post exercise respectively, providing that sufficient CHO is ingested (2.5 g·kg\textsuperscript{-1}) during the recovery period. It is possible that the relatively higher muscle glycogen content in the initial post exercise period with immediate ingestion may lead to a comparatively reduced rate of glycogen synthesis after this time. This finding signifies that, despite glycogen storage being most rapid immediately following exercise, athletes need not consume CHO immediately after training or competition to restore glycogen levels, providing they ingest sufficient CHO in the six hours post exercise and are not required to exercise again within eight hours\textsuperscript{37}.

Although researchers have been unable to agree on the role of IMTG during exercise, recent studies have shown IMTG stores to be a valuable aid during post exercise glycogen recovery providing substrate for metabolism to allow the resynthesis of glycogen. Despite a well controlled, rich CHO diet (65-70 % kcal as CHO, 8-10 g CHO · kg · day, ~570 g/day) beginning one hour post glycogen depleting exercise and continued until 42 hours post exercise, IMTG concentrations that remained unchanged during exercise, decreased significantly during the first three hours post exercise and reached a nadir 18 hours after the cessation of exercise (20% lower than resting values). While the mechanism is still unknown, it appears that muscle glycogen resynthesis has high priority during recovery such that utilization of lipids (>50%) is necessary to cover energy
expenditure in muscle with IMTG accounting for a substantial part of the high lipid oxidation\textsuperscript{32}.

In summary, post exercise muscle glycogen synthesis can be augmented by many factors. The rate of resynthesis can be hastened (greatest effect seen < 40 min post exercise) if a protein supplementation is added to the ingestion of CHO post exercise. However, altering the frequency of CHO consumption (~every 30 min) limits the effect of protein supplementation and results in similar rate of resynthesis by four hours post-exercise. Since increased muscle glycogen content is associated with decreased muscle glucose uptake, delaying the ingestion of CHO by two hours has no effect on long term muscle glycogen storage, providing that sufficient CHO is ingested during the recovery period. IMTG stores have been shown to play an important role in the rate of glycogen resynthesis by providing muscle with substrates during the glycogen resynthesis period.
Methodology

One recreationally competitive male subject (38 yr.) completed a half Ironman triathlon (1.9 km swim, 90 km bike, 13.1 km run, Grand Columbian, Coulee City, WA). Prior to the race, the subject underwent descriptive testing to determine peak oxygen uptake (VO\textsubscript{2 peak}) and ventilatory threshold (VT) on an electronic cycle ergometer (Velotron, Seattle, WA) and motorized treadmill (Quinton treadmill, Seattle, WA). Characteristics of the subject is shown in Table one. In addition to the maximal exercise testing, linear regression equations were established for the relationship between watts and running speed pace relative to submaximal, steady state measures of VO\textsubscript{2} and VCO\textsubscript{2}. These regression equations were then used to quantify total energy expenditure and whole body substrate oxidation during the cycle and run portions of the race. The regression equation for the cycle was established using a progressive resistance fluid trainer (CycleOps, Madison, WI) and the subjects own time trial bicycle equipped with the SRM power system (Colorado Springs, CO). A similar equation was established on a motorized treadmill for the run calculations.

Laboratory Pre testing

After a thorough warm up, in a CHO fed state, performed on a calibrated Quinton treadmill (Seattle, WA), the subject began the max test until volitional fatigue. Expired gases were collected using a calibrated metabolic cart (Parvomedics, Inc., Salt Lake City, UT) and analyzed at 15-second intervals. Ventilatory threshold (VT) was determined using a combination of the V-slope method, the ventilatory equivalent method and the
excess CO\textsubscript{2} method\textsuperscript{12}. Heart Rate was recorded every five seconds using a Polar HR
monitor (Polar S810i, Finland).

Cycling Testing

Peak VO\textsubscript{2} was measured for the subject using a ramp protocol (60 W \cdot min\textsuperscript{-1}) on
an electronically braked cycle ergometer (Velotron, Seattle, WA). Swimming prior to
cycling has been shown to have no significant performance effect on subsequent 3 hour
cycling performance in ultraendurance triathletes\textsuperscript{35}. Therefore, prior to the start of the
test, the subject was well fed and rested. Expired gases and VT were collected and
analyzed as indicated above. The subject underwent a submaximal cycling test, in a
rested and CHO fed state, with four 5-min steady-state stages of increasing power outputs
(50, 100, 200, and 300 W). Expired gases and HR were collected as indicated above.

Experimental Protocol

Pre Race

Approximately 90 minutes prior to the start of the race, the subject underwent the
first of three muscle biopsies to the right \textit{vastus lateralis} under local anesthesia using the
Bergstrom biopsy needle\textsuperscript{3}. Muscle samples were immediately frozen in liquid nitrogen
and stored for later analyses. After the biopsy, the subject was weighed in his racing gear
(tri shorts, watch, and HR monitor). Prior to the start of the race, the subject consumed
2,394 KJ, 110 g CHO (1.4 g CHO\textperiodcentered kg).

Race

Energy intake during the race was collected and is shown in Table 2. HR was
recorded every five seconds (Polar S810i, Finland), power was recorded every 15
seconds (SRM Power Systems, Colorado Springs, CO), and running speed (min/mile) was collected throughout the race.

Post Race

Immediately post race, the subject was weighed in his racing gear and a second biopsy was taken from a second incision 2 cm proximal to the pre-exercise incision. The muscle was prepared and stored as indicated above. After the post-race biopsy, the subject consumed a standardized diet that consisted of 471g CHO, 15g Fat, 64g Protein, which included scheduled liquid CHO sources (Gatorade energy drink, 0.22 g CHO/ml) and a meal provided by the race. Total carbohydrate intake during this four-hour refeeding period was 6.3 g kg\(^{-1}\). Four hours post race, a third biopsy was obtained (from a third incision 2 cm proximal to the post-exercise incision) as indicated above. After the third biopsy, body weight was again recorded with the subject wearing racing gear.

Sample Analyses

Muscle glycogen was analyzed using an enzymatic spectrophotometric method (Infinity glucose (HK) liquid stable reagent, ThermoTrace Ltd.) after tissue preparation. Samples (17.9 +/- 9.3 mg wet weight) were weighed upon removal from a -80\(^{\circ}\)C freezer. Samples were placed in 1ml, 1N HCL solution and homogenized using a manual mortar and pestle tissue grinder. Once homogenized, samples were incubated at 95.6\(^{\circ}\)C for three hours. After the incubation, 0.5ml, 1N NaOH was added to 0.5ml of boiled tissue sample to normalize pH. Samples were analyzed in triplicate against known glycogen and glucose controls run at the same time. Muscle glycogen concentrations were expressed in mmol · kg\(^{-1}\) wet weight of muscle. Rates of muscle glycogen resynthesis were expressed as mmol · kg\(^{-1}\) · hr\(^{-1}\) wet weight of muscle and calculated from the following equation:
Rate\((G_{\text{post}} - G_{\text{pre}})/t\), where \(G_{\text{post}}\) is the glycogen concentration at 4 hours post feeding, 
\(G_{\text{pre}}\) is the glycogen concentration immediately post exercise, prior to feeding, and \(t\) is the time between biopsies.

**Table 1.** Subject descriptive data

<table>
<thead>
<tr>
<th>Age</th>
<th>Ht (cm)</th>
<th>Wt (kg)</th>
<th>Peak VO(_2) Bike (l(\cdot)min(^{-1}))</th>
<th>Peak VO(_2) Run (l(\cdot)min(^{-1}))</th>
<th>VT Bike (l(\cdot)min(^{-1}))</th>
<th>VT Run (l(\cdot)min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>185.4</td>
<td>78.8</td>
<td>4.83</td>
<td>4.92</td>
<td>3.01</td>
<td>3.42</td>
</tr>
</tbody>
</table>

**Table 2.** Energy intake

<table>
<thead>
<tr>
<th></th>
<th>Pre Race</th>
<th>During Race</th>
<th>4 Hour Post Race</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calories (KJ)</td>
<td>2,386</td>
<td>4,861</td>
<td>9546</td>
</tr>
<tr>
<td>CHO (g)</td>
<td>110 g</td>
<td>307.91 g</td>
<td>471 g</td>
</tr>
</tbody>
</table>

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References


Abstract

PURPOSE: The purpose of the study was to describe the degrees of muscle glycogen depletion and resynthesis in response to a half Ironman triathlon. METHODS: One male subject (38 yr.) completed the Grand Columbian half Ironman triathlon (1.9 km swim, 90 km bike, 21.1 km run). Three muscle biopsies were obtained from the subject's right vastus lateralis (pre-race, immediately post-race, and four hours post-race). Pre and post-race body weight was recorded, in addition to macronutrient consumption before, during, and after the race. Energy expenditure and whole body substrate oxidation was estimated from linear regression established from laboratory trials (watts and run pace relative to \(\text{VO}_2\) and \(\text{VCO}_2\)). RESULTS: Overall finish time for the race was 4:48:53 (33:33 swim, 2:43:11 bike, 1:28:40 run). Body weight decreased 3.8 kg from pre to post-race. Estimated CHO energy expenditure (EE) was 10,003 KJ (641g CHO, 88% of cycle EE) for the bike segment and 5,759 KJ (369g CHO, 86% of total run EE) for the run segment of the race. A total of 308g of exogenous CHO (liquid and gel) was consumed (1.21 g CHO/min). Muscle glycogen decreased from 227.1 pre-race to 38.6 mmol kg\(^{-1}\) wet wt. post-race. During the four hours post-race, a mixed diet was consumed (471g CHO, 15g fat, 64g protein) which included liquid CHO sources and a meal. The calculated rate of muscle glycogen resynthesis was 4.1 mmol kg \(\cdot\) hr\(^{-1}\) wet wt.\(^{-1}\).

CONCLUSION: The completion of a half Ironman triathlon is dependent on a high rate of muscle glycogenolysis, which demonstrates the importance of exogenous carbohydrate intake during the race. In addition, rates of muscle glycogen resynthesis may be dampened by the eccentric damage resulting from the run portion of the race.
Introduction

A triathlon is a distinct sporting event combining three disciplines (swimming, cycling, and running) that impose unique metabolic and nutritional concerns for the working muscle depending on the duration of the event. The half Ironman triathlon consists of a 1.9km swim, followed by a 90km cycle, and 21.1km run. Fatigue during prolonged, intense exercise is associated with glycogen depletion in working skeletal muscles\(^5\). Although endogenous glycogen stores are limited, pre-race diet can increase these stores, proper training can attenuate the utilization, and feeding during the race may decrease the velocity of muscle glycogen loss. Muscle glycogen is the most important substrate for contracting muscle during moderate to heavy exercise\(^5\). The purpose of this study was to describe the degrees of muscle glycogen depletion and resynthesis in response to a half Ironman triathlon.

Methodology

One recreationally competitive male subject (38 yr.) completed a half Ironman triathlon (1.9 km swim, 90 km bike, 13.1 km run, Grand Columbian, Coulee City, WA). Prior to the race, the subject, in a carbohydrate fed state, underwent descriptive laboratory testing to determine peak oxygen uptake (VO\(_2\) peak) and ventilatory threshold (VT) on an electronically braked cycle ergometer (Velotron, Seattle, WA) and motorized treadmill (Quinton treadmill, Seattle, WA). In addition to the maximal exercise testing, linear regression equations were established for cycle watts and treadmill running pace (at 1% grade to account for metabolic equivalent of wind resistance) relative to submaximal, steady state measures of VO\(_2\), VCO\(_2\), and HR. These regression equations were then
used to quantify total energy expenditure and whole body substrate oxidation during the cycle and run portions of the race.

*Pre Race*

Approximately 90 minutes prior to the start of the race, after eating breakfast, a pre-race muscle biopsy was obtained from the right *vastus lateralis*\(^1\). Muscle samples were immediately frozen in liquid nitrogen and stored at -85°C for later analyses. After the muscle biopsy a measure of body weight was obtained. Macronutrient consumption of breakfast was measured and recorded.

*Race*

During the entire race, macronutrient consumption patterns were recorded from a pre-established intake plan amounting to approximately 1.2 g min\(^{-1}\). Deviations from the intake plan were recorded from subjects dietary recall during the race. In addition, cycle power output (SRM power systems, Colorado Springs, CO) and HR (Polar S810i, Finland) was continually measured. Running pace was monitored by the subject using a digital running watch and mile lap split recordings.

*Post Race*

Immediately after the race, a post-race measure of body weight was obtained in the same clothing as pre-race. A post-race biopsy was then obtained (from a second incision 2 cm proximal to the pre-exercise incision) after which the subject consumed a standardized diet (total = 471g CHO, 15g Fat, 64g Protein), which included hourly liquid CHO sources (Gatorade energy drink, 0.22 g CHO/ml) and a meal provided by the race. Total carbohydrate intake during this four-hour refeeding period was 6.3 g kg\(^{-1}\) (1.6 g·kg·hr).
Four hours post race, a third biopsy was obtained (from a third incision 2 cm proximal to the post-exercise incision) as indicated above.

Sample Analyses

Muscle glycogen was analyzed using an enzymatic spectrophotometric method as previously described.®

Results

Overall finish time for the race was 4:48:53 (33:33 swim, 2:43:11 bike, 1:28:40 run).

The subject averaged 230 W (110% VT, 68% VO₂ peak) for the cycle portion of the race, and 14.24 km/hr (101% VT, 70% VO₂ peak) for the running portion of the race. Body weight decreased 3.8 kg from pre to post-race. The ambient air temperature fluctuated throughout the race and was 13.9° C at the 09:30 start, 22.2° C at 12:00, and 23.9° C at the finish. Estimated CHO energy expenditure (EE) was 10,003 KJ (641g CHO, 88% of total cycle EE) for the bike segment and 5,759 KJ (369g CHO, 86% of total run EE) for the run segment of the race. Two hours prior to the race, a total of 110g CHO were consumed. During the race, 308g CHO (sports drink and gel products) were consumed, averaging 1.2 g·min⁻¹ during the run and bike portions of the race. Total run and bike CHO EE was estimated at 15,762 KJ (1,010 g), and energy intake during the race was estimated at 4,895 KJ (418 g), or 31% of the total CHO EE.

Muscle glycogen demonstrated an 83% decrease from 227.1 pre-race to 38.6 mmol kg⁻¹ wet wt. post-race. During the four hours post-race, muscle glycogen demonstrated an increase to 54.90 mmol kg⁻¹ wet wt., 24% of pre-race values, with a calculated rate of muscle glycogen resynthesis of 4.1 mmol kg⁻¹ wet wt.·hr⁻¹.
Discussion

The main findings from this case study indicate that the completion of a half Ironman triathlon is associated with a high rate of whole body CHO oxidation and muscle glycogenolysis. Furthermore, this demonstrates the importance of pre-race nutritional strategies to maximize glycogen storage coupled with an aggressive exogenous CHO intake schedule during the race to maintain CHO oxidation and exercise intensity.

Past research has suggested a feeding schedule amounting to 60-70 g hr\(^{-1}\) of CHO during prolonged exercise because maximal rates of exogenous CHO oxidation average 1.0 to 1.1 g/min\(^7\). However, if the CHO solution includes a mixture of 3 parts glucose, 1 part fructose, a higher rate of exogenous CHO oxidation is possible (20-50% increase in oxidation to approximately 1.50 g min\(^{-1}\)) compared to the ingestion of an isocaloric glucose solution\(^6\). It appears that glucose and fructose are absorbed by different intestinal transport mechanisms, which may lead to faster transport and subsequent oxidation of exogenous CHO sources by the active skeletal muscle. This type of strategy to maximize exogenous CHO oxidation may be crucial during this type of long duration bout of exercise. Although the importance of exogenous CHO are clear, we cannot conclude from this descriptive data whether the intake of exogenous CHO decrease the rate of muscle glycogenolysis. Although the consumption of exogenous CHO (1.15 g min\(^{-1}\) glucose and fructose mixture, 3:1) may have improved performance during the race, there was a noticeable decrement in running performance. Average split times were 6:17, 6:44, and 7:10 min/mile\(^{-1}\) for miles 1-3, 6-8, and 10-13, respectively. This fatigue may be a combination of dehydration (4.9% decrease in body weight), CNS fatigue, diminished muscle glycogen, and/or elevated core body temperature. However, fatigue was not
likely related to inadequate exogenous CHO intake as it approached the reported maximal rates previously recommended\textsuperscript{6}.

Total CHO availability (g) was supplemented by the combination of the pre-race meal (110 g CHO) and the feedings during the race (308 g CHO) which represented 41% of the total CHO oxidized during the cycle and run portions of the race, not accounting for additional CHO oxidation during the swim. This is in agreement with previous findings reporting that high rates of CHO oxidation can be maintained during the latter stages of prolonged continuous exercise when muscle glycogen stores are very low\textsuperscript{3}. CHO supplementation during prolonged exercise can partially compensate for the reduction of endogenous CHO stores and delay fatigue by maintaining plasma glucose availability. However, it appears that consuming exogenous CHO at a rate of approximately 1.2 g min\textsuperscript{-1} cannot fully compensate for the negative effects of glycogen depletion as evidenced by the impaired running performance late in the race. Therefore, the possibility of an endogenous CHO sparing effect due to the consumption of exogenous CHO appears unlikely under competitive racing conditions\textsuperscript{3}.

In addition, researchers have shown that the effects of eccentric muscle damage may dampen the rates of muscle glycogen resynthesis. The calculated rate of muscle glycogen resynthesis was 4.1 mmol kg\textsuperscript{-1} \cdot hr\textsuperscript{-1} wet wt. The prolonged eccentric contractions during the run portion of the race may account for the low rate of muscle glycogen resynthesis reported in comparison to some of our earlier work with a high intensity cycling protocol, which demonstrated a much higher rate of muscle glycogen resynthesis (10.6 mmol \cdot
Similar results have suggested that eccentric contractions dampen the rate of muscle glycogen resynthesis when the traumatized muscle is penetrated with inflammatory cells, which oxidize glucose. Eccentric damage presents a competition between the inflammatory cells and the glycogen-depleted muscle fibers for blood glucose, reducing the amount of available glucose for muscle glycogen storage.

Researchers have additionally shown that CHO intake during prolonged exercise may diminish postexercise muscle glycogen resynthesis rates, when compared to prolonged exercise in the fasted state. The mean rate of muscle glycogen resynthesis during the initial 4 h recovery period after the fasting exercise bout was found to be ~3-fold higher than after exercise combined with carbohydrate ingestion, perhaps due to enhanced insulin action.

Conclusion
The main findings indicate that the completion of a half Ironman triathlon is dependent on a high rate of whole body CHO oxidation and muscle glycogenolysis, which demonstrates the importance of pre-loading adequate exogenous CHO intake during the race. In addition, rates of muscle glycogen resynthesis may be dampened during the recovery from such an event by the eccentric damage resulting from the run portion of the race.

Acknowledgements
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References


