Lore of Running

Chapter 3

Energy systems and running performance

- Part 1: Types of Fuel & Digestion
- Part 2: Storage
- Part 3: Limits to Endurance Performance
- Part 4: Factors that affect which fuel is used
- Part 5: Maintaining fuel
- Part 6: Lactic Acid
- Part 7: Training responses

Energy

- Different Forms
    - Nuclear
    - Heat
    - Mechanical
    - Chemical
    - Light Electrical The capacity to do work.
  - Units: Joule
- Work (thermodynamics) is the transferring of energy from one object to another
  - Mechanical work: Application of a force over a distance
    - W = Fd

Calorie

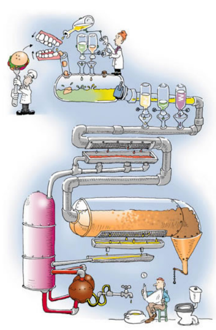
- Calorie
  - A unit of heat
  - 1 Calorie = 4184 J
    - Large calorie … kcal
  - The amount of heat needed to change the temperature of 1 kg water (1 L) from 14.5º C to 15.5º C.
    - If the energy were released of a substance with a caloric value of 300 Calories …
      - The temperature of 300 L of water would be raised 1º C

Energy

- Food is stored energy.
- A piece of buttered toast has about 315 kJ (~75 Calories) of energy.
  - Jog for 6 minutes
  - Bike for 10 minutes
  - Light a 60 W light bulb for 1.5 hours

How the body uses food

- Digestion
  - The process by which food is broken down mechanically and chemically in the gastrointestinal tract and converted into absorbable forms.
    Taber's



Digestion

- Mouth
- Esophagus
- Stomach
  - Some small molecules (e.g., alcohol) can be absorbed into circulatory system.
- Small intestines
  - The majority of digestion and absorption takes place here.
  - Secretions from liver and pancreas
  - Carbohydrates, fats, and proteins absorbed in upper/middle parts of small intestine.
- Large intestines
  - Cecum, colon (ascending, transverse, descending), rectum
  - Absorb water

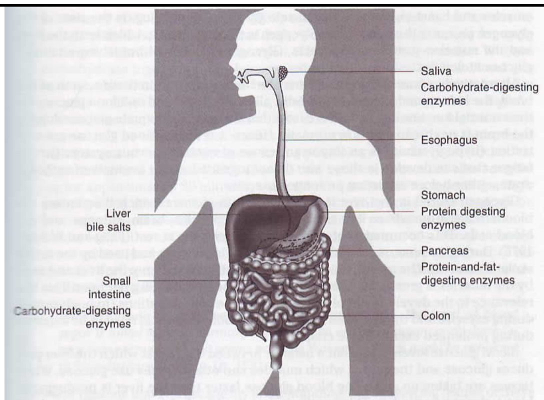


Figure 3.1 The passage and digestion of food in the intestine.

Carbohydrate

- Composed of carbon and water.
- Three types
  - Monosaccharides
    - More than 200 monosaccharides
    - Glucose, fructose, galactose
  - Oligosaccharides
    - Disaccharides
      - Combination of two monosaccharide molecules
        - » Sucrose: glucose + fructose
        - » Lactose: glucose + galactose
        - » Maltose: glucose + glucose
      - Simple sugars
      - e.g., brown sugar, corn syrup
  - Polysaccharides
    - Three or more simple sugar molecules
    - Starch
    - Fiber
    - Glycogen

Carbohydrates

- Absorbed carbohydrates transported to liver.
- Glucose can be stored as glycogen in liver or transported to skeletal muscle (muscle glycogen).
    - Glyconeogenesis: Formation of glycogen from noncarbohydrate sources
    - Glycogenesis: Formation of glycogen from carbohydrate sources
  - Glycogen is the only form carbohydrates are stored.
- Glucose is used by brain, kidney, red blood cells
- Glycogen stored in liver can be broken down to glucose and delivered at a rate of about 10 g per hour at rest and 60 g per hour during exercise.
    - Glycogenolysis: Breakdown of glycogen to glucose

Hypoglycemia

- Low levels of glucose in blood
- History
  - 1924 Boston Marathon
    - Postrace blood glucose concentrations were decreased in all runners.
    - Runners with low blood glucose levels presented with "asthenia, pallor and prostration."
      - Loss of strength, lack of color, absolute exhaustion
      - Following year runners used high-carbohydrate pre-race meal
    - Harvard Fatigue Lab
      - Dogs (Joe and Sally) ran without exhaustion for 24-hours when feed sweets
      - Without, both became exhausted
- Related to fatigue

Fats

- Three groups
  - Simple fats
    - Triglycerides: the most plentiful fat in the body (~95% of fat in body)
      - Three fatty acid molecules attached to one glycerol molecule
  - Compound fats
    - Simple fat combined with other chemicals
      - E.g., lipoproteins (transport fat in blood)
  - Derived fats
    - Fats derived from simple and compound fats
    - e.g., cholesterol

Fat

- Digested in small intestines
  - enzymes from pancreas
- Stored as triglyceride
  - adipose tissue and in muscle
  - To be used as energy
    - fatty acid must be separated from glycerol molecules
    - Free fatty acids and glycerol transported via circulatory system (carrier: albumin)

Protein

- Greek: 'of prime importance'
- Combinations of amino acids make up proteins
  - 20 amino acids required by the body
  - 8(9) cannot be synthesized in the body (i.e., essential)
- Digested to yield amino acids.
  - Amino acids transported to liver.
  - Used as an energy source during prolonged exercise (e.g., > 3 or 4 hours)
    - ~2-8%

Summary – Part 1

- Types of fuel
- Digestion

Part 2 – Storage of Fuels

How the body stores fuel

- Water accounts for up to 64% of total body weight.
- Fat is the largest energy store in the body.
  - Carbohydrate stores are relatively small.
    - If only carbohydrate was used as a fuel during a marathon, the storage would last about 2 hours (fat: 59 hours).

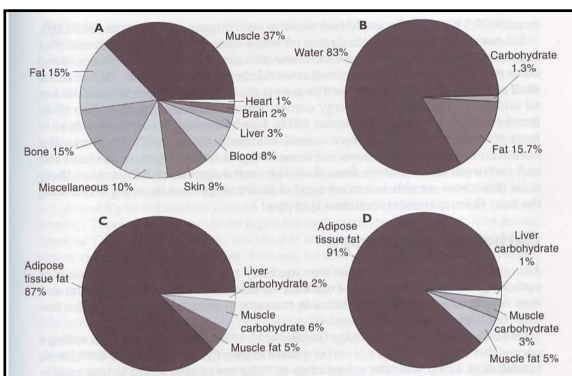
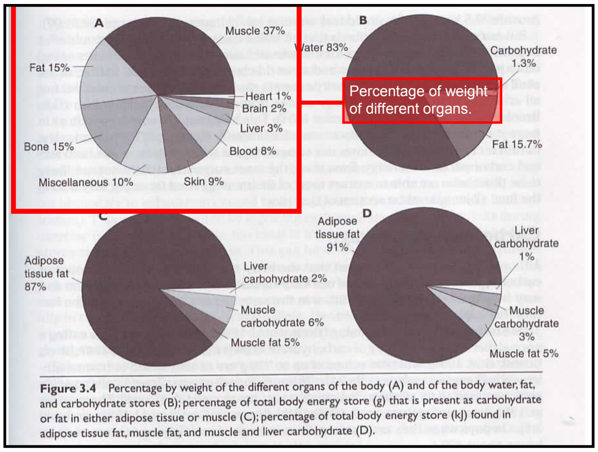


Figure 3.4 Percentage by weight of the different organs of the body (A) and of the body water, fat, and carbohydrate stores (B); percentage of total body energy store (g) that is present as carbohydrate or fat in either adipose tissue or muscle (C); percentage of total body energy store (kJ) found in adipose tissue fat, muscle fat, and muscle and liver carbohydrate (D).



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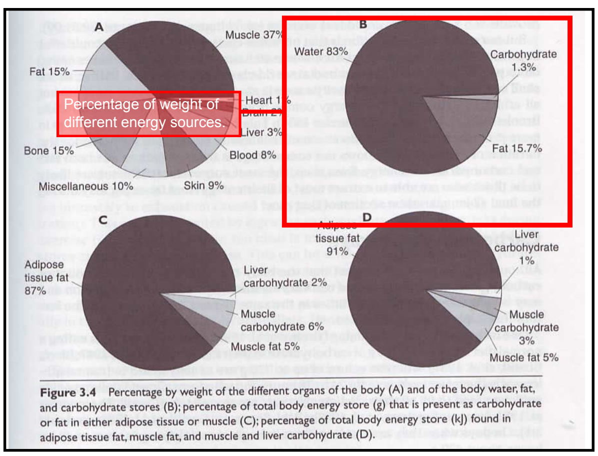

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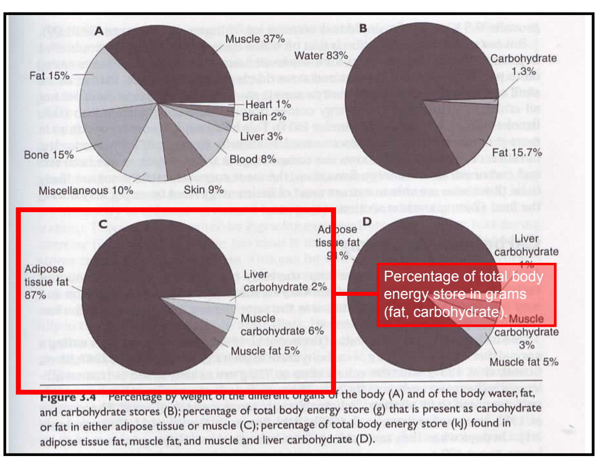

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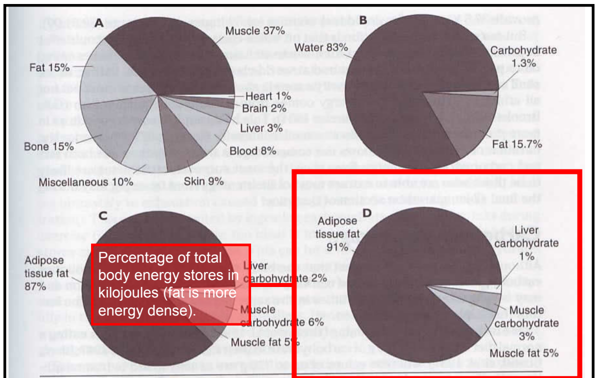

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Carbohydrate Storage

- The amount of carbohydrate that can be stored varies between people
  - Influenced by training
    - Untrained: 280 g
    - Trained: 720 g
  - Influenced by diet
    - Table 3.1

Storage

- Fat
  - Body composition for endurance runners
    - Lower %body fat: e.g., 4-7%
- Protein
  - Are present in all cells
    - Cell walls, filaments, structural, compounds in blood …
    - Protein storage is tightly regulated
      - Weight lifting
    - Starvation leads to a reduction in protein stores.

Storage

- Endurance athletes want to know:
  - How to optimize fuel storage.
    - carbohydrates
  - How to replenish fuel storage during and after training sessions and races.
- The next section looks at factors that influence storage of fuel.
  - An emphasis is placed on storage of carbohydrates vs. fat.

Factors Affecting Fuel (Carbohydrate) Storage

- Carbohydrate storage is greater for trained vs. untrained people.
- Endurance athletes commonly use:
  - Deplete
    - Through exercise
  - Diet
    - What is eaten regularly vs. restricting calories
  - Replenish
    - When an athlete eats (i.e., during, after exercise)

Factors affecting *depletion* of carbohydrates

- Exercise intensity and duration
  - The higher the intensity, the more rapid rate of glycogen use.
  - Continuous exercise at 70-85% VO_{2max} for periods longer than 2 hours results in the greatest muscle glycogen depletion.

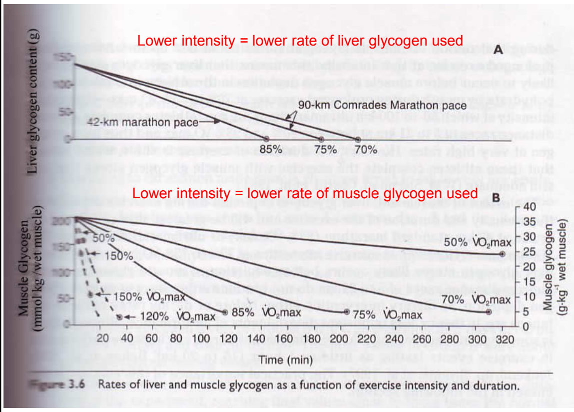
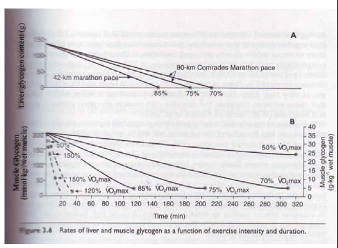
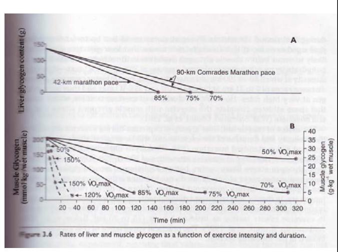


Figure 3.6 Rates of liver and muscle glycogen as a function of exercise intensity and duration.

- Less is known about liver glycogen depletion vs. muscle glycogen depletion.
- Rate of liver glycogen depletion linear and dependent on intensity.
- Can be depleted in 2-3 hours.

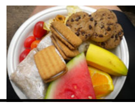


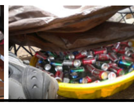
- Muscle glycogen levels fall over time.
- Rate of depletion of muscle glycogen is initially rapid until about 1/3 levels are reached.
  - Rate is dependent on intensity of exercise.
  - Muscle glycogen can be depleted rapidly using intermittent exercise (dotted lines).
  - Continuous exercise at 70-85% VO_{2max} results in greatest depletion.
  - Can be depleted in 2-4 hours.



Factors that affect food storage: *Diet*

- Eating a high-carbohydrate diet
  - Glucose produced by liver is used to return blood glucose and muscle glycogen stores back to normal.
  - The resynthesis of glycogen is aided by a high-carbohydrate diet.
    - …but athletes who think they are on high-carbo diet may not be
  - Does a pre-race carbohydrate depletion/replenishing program work?
    - Carbo-loading





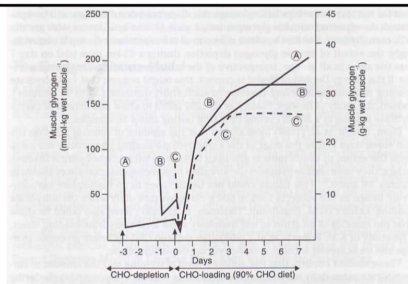
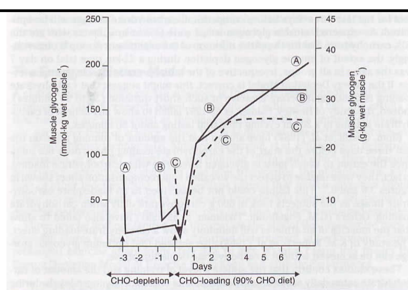


Figure 3.7 The effects of the popular carbohydrate-depletion/carbohydrate-loading exercise diet regime on muscle glycogen levels. Three groups of exercisers are represented by A, B, and C.
Ahlborg, Bergström, et al. (1967a, p. 91).

Classic study on carbohydrate loading.

The results of this study have been used to support the idea of carbo-loading.



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- Group A:
  - Exercised to exhaustion (day -3)
  - Ate high-fat-protein, low carb for 3 days
  - Exercised to exhaustion
  - Ate high carb diet for 7 d
- Group B:
  - Exercised to exhaustion (day -1)
  - Ate high-fat diet (1 day)
  - Exercised to exhaustion (day 0)
  - Ate high carb diet for 7 d
- Group C
  - Exercised to exhaustion (day 0)
  - Ate high-carb diet for seven days

- Key points:
  - Exercising to exhaustion reduced muscle glycogen levels.
  - Minimal glycogen resynthesis on high-fat-protein diet for Groups A and B (pre day 0).
  - Muscle glycogen levels
    - Peaked for Group B
    - Continued to rise for Group A
  - Subjects were relatively unfit.

Carbo-loading

- Depletion / carbohydrate loading diet similar to Group A.
  - 'carbo-loading' pre-race parties
    - Eating a lot 1 or 2 days before an event is not a replication of the study
  - 7 days are needed (based upon these results)
  - Remember … subjects were unfit
- Key points:
  - Different manipulations of carbo/fat diets can be used to maximize muscle glycogen
  - The main determinants of muscle glycogen levels during carbo loading are the
    - 1) athlete's level of training
    - 2) the amount of carbohydrate eaten daily

Carbo-loading with trained athletes

- Sherman, Costill, et al. (1981)
  - Had three groups of subjects go through depletion/reloading protocol.
  - Tested muscle glycogen stores
  - Bottom line: traditional depletion/loading protocol did not offer advantages to trained athletes.
  - Eating high-carbohydrate diet during the 3-days before competition was critical.

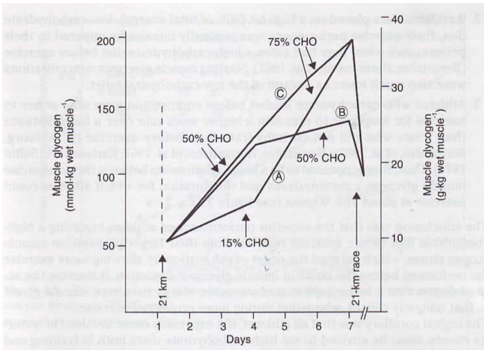
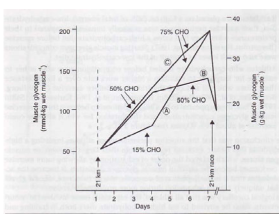


Figure 3.8 Muscle glycogen changes in trained athletes undergoing the modified carbohydrate (CHO)-loading regime.
From Sherman, Costill, et al. (1981, p. 116)

- Three groups (trained):
  - A. 15% Carbohydrate 3 days
    75% Carbohydrate 3 days
  - B. 50% Carbohydrate
  - C. 50% Carbohydrate 3 days
    75% Carbohydrate 3 days
  - D. 5 days of tapered running @75 VO_{2max} (90, 40, 40, 20, 20 min) + 1 day of rest.
- Groups A and C reached same levels pre-race.
  - Eat high carbohydrate diet at least 3-days pre-race.
- Extent of muscle glycogen after 21 km race the same.
- No difference in race performance
- Carbohydrate loading may not be as effective for trained vs. untrained athletes.



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Summary – Part 2

- Storage
  - Fats
  - Glucose
    - Liver
    - Muscle
    - Blood
  - Carbo-loading

Part 3: Limits to Performance

- Why do people stop at the end of a maximal effort graded exercise test?
- Why do athletes collapse at the end of an Ironman or marathon?
- What limits the ability to cover endurance distance in the shortest time?
- How do you minimize the influence of fatigue?
  - '… prevent fatigue …'

Limits to Performance

- Central Governor Model: Reduced muscle recruitment

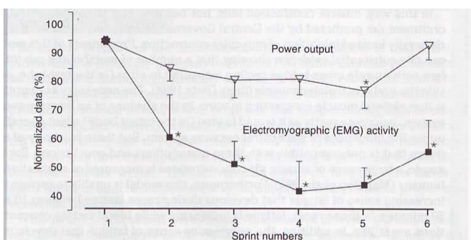


Figure 3.3 Changes in power output and electromyographic (EMG) activity in the vastus lateralis muscle during six consecutive 1-minute sprints during 60 minutes of all-out cycling.
Redrawn from data of Kay et al. (2001, p. 118). (c) 2001 by Springer-Verlag, Heidelberg. Adapted by permission.

Limits to Performance

- Energy Supply Model
  - Performance is limited by the availability of substrate and capacity of metabolic pathways
    - Anaerobic
    - Aerobic
  - Superior endurance performance is a function of being able to produce ATP aerobically.
    - Fatigue would result by the breakdown of the metabolic pathway (e.g., lack of available substrate)
      - *ATP would not be produced*
      - *Rigor would result*
  - Noakes questions the validity of this argument
    - ATP levels are protected since ATP levels do not drop below 60% of resting levels.

Limits to Performance

- Muscle glycogen?
  - This makes sense because glucose is needed for aerobic production of ATP.

Energy-Depletion Model

- There is evidence supporting the idea that endurance performance is limited by muscle glycogen levels.
  - Muscle glycogen levels were low in athletes when exercising to exhaustion at 60-80% VO_{2max}.
    - Hypothesis: Low levels contribute to fatigue
  - Athletes on high-fat diet had lower exercise performance than those on high-carbohydrate diet.
    - Starting level of muscle glycogen lower for high-fat diet.
  - Athletes who "carbo-loaded" out performed those who did not.
    - Observation: There is a linear relationship between pre-exercise muscle glycogen and duration of exercise.
- Hypothesis: Superior endurance performance resulted from higher pre-exercise muscle glycogen levels which delayed exhaustion (onset of muscle glycogen depletion).

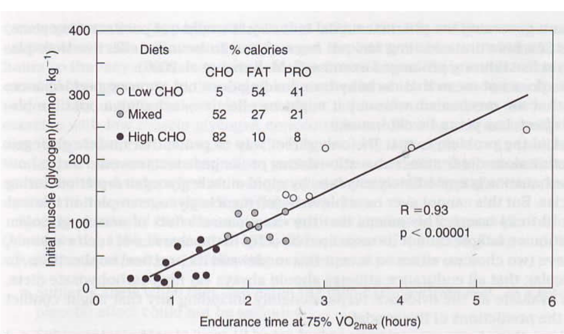
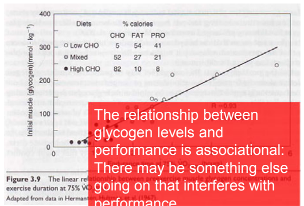


Figure 3.9 The linear relationship between preexercise muscle glycogen concentrations and exercise duration at 75% $\dot{V}O_2$max.
Adapted from data in Hermansen, Hultman, et al. (1967).

- Three groups (trained):
  A. Low Carbohydrate diet
  B. Mixed diet
  C. High Carbohydrate diet
- Preexercise levels of muscle glycogen were related to time to exhaustion at 75% VO2max.



The relationship between glycogen levels and performance is associational: There may be something else going on that interferes with performance.

- placebo effect
- central (e.g., glycostat)
- rising body temperature
- ….?

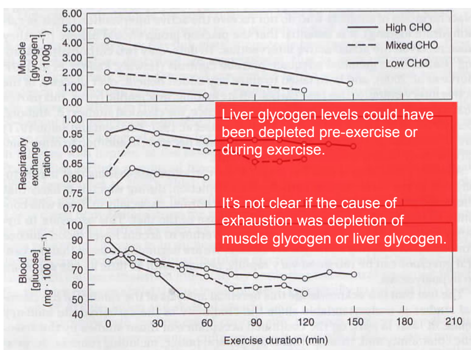


Figure 3.10 Hypoglycemia occurs rapidly in subjects eating a low-carbohydrate diet before exercise.
Data from Bergström, Hermansen, et al. (1967).

Liver glycogen levels could have been depleted pre-exercise or during exercise.

It's not clear if the cause of exhaustion was depletion of muscle glycogen or liver glycogen.

Challenges

- There is no direct evidence that any one phenomenon (e.g., muscle glycogen depletion) causes exhaustion.
  - The model is based upon the association of muscle glycogen and exhaustion.
  - There may be some other phenomenon that happens at the same time as muscle glycogen depletion.
    - Reduced blood glucose concentration (liver glycogen depletion leads to hypoglycemia)
    - Rising body temperature
    - Stretch-shortening fatigue
    - Central fatigue
    - Placebo effect
  - ATP depletion is not present at exhaustion.
    - …which means ATP is available (i.e., rigor is not present).

Challenges

- The key to carbo-loading may be the three days of carbohydrate depletion.
  - Does this pre-program the Central Governor to accept lower blood glucose concentrations?
  - Evidence building that athletes can adapt to different dies (e.g., high-fat) without sacrificing endurance performance.
    - The hypothesis that exhaustion occurs at low muscle glycogen levels is not tenable for athletes who have adapted to a high-fat diet.

Carbohydrate

- Having a sufficient level of muscle glycogen is important to endurance performance.
  - Fats?
  - “Metabolic flexibility”
- The mechanism of fatigue is not known.
- It is not clear what role pre-exercise muscle glycogen levels plays in fatigue.
  - Low levels during exercise may trigger some other mechanism that leads to fatigue.
  - Low levels during exercise does not always lead to fatigue.

Carbo-loading

- The information presented should not be taking that carbo-loading does not work.
- The information should be taken to understand that:
  - The mechanism explaining the relationship between performance and carbohydrate levels is not known.
- It is not clear how placebo effect influences studies.
- Does carbohydrate loading improve endurance performance by delaying the onset of liver glycogen depletion (which causes hypoglycemia)?

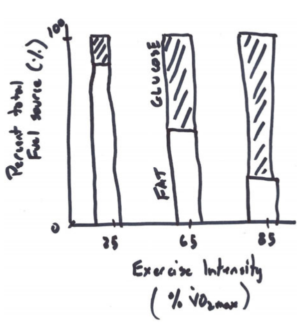
Summary – Part 3

- Limits to performance
  - Central Governor Model
  - Fuel
    - Availability
    - Energy depletion

Part 4
Factors that affect which fuel is used

- When intensity of exercise increases, carbohydrates become more important for energy production.
  - Classic: Only carbohydrates are used at intensities greater than 95% VO_{2max}
    - It is possible that intramuscular triglycerides are used at high intensities as well.
    - …but, the take home point is carbohydrates are the principle fuel at high intensities.

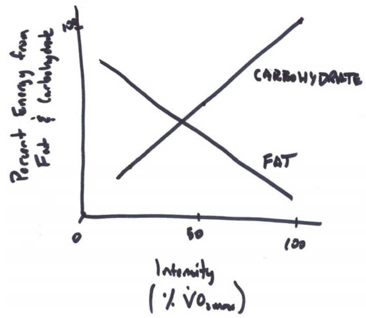
Effect of Exercise Intensity on Muscle Fuel Source



Fats
- Triglycerides: Three fatty acids + glycerol
- Free Fatty Acid: Fatty acids not combined with anything.

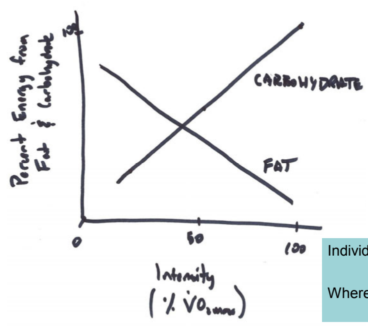
Glucose
- Blood glucose
- Muscle glycogen

Intensity



Bottom line: Carbohydrates are used as the primary fuel at higher intensities.

Intensity



Bottom line: Carbohydrates are used as the primary fuel at higher intensities.

Individual variability

Where does ‘cross-over’ occur?

Variability

- Individuals can respond uniquely.
  - Noakes: not all subjects were able to complete a 3-hour bout of exercise after carboloading without some carbohydrate during exercise.
    - Different people may be ‘fat-burners’ or ‘carbohydrate-burners’.
    - Goedecke, St. Clair Gibson, et al. (2000) compared metabolism during rest and during exercise.

Respiratory Exchange Ratio

- RER: The ratio of CO_2 production to O_2 consumption.
- Used as an indication of substrate utilization.
- RER= VCO_2/VO_2
  - A value closer to 1.00 = glucose as primary fuel.
    - Glucose = $C_6H_{12}O_6$

      $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_20$

      RER = VCO_2/VO_2 = 6 CO_2 / $6O_2$ = 1.00
  - A value closer to 0.7 = fat as primary fuel
    - Fat (palmitic acid) = $C_{16}H_{32}O_2$

      $C_{16}H_{32}O_2 + 23O_2 \rightarrow 16CO_2 + 16H_2O$

      RER = VCO_2/VO_2 = 16 CO_2 / $23O_2$ = 0.70
  - A value greater than 1.00 = lactic acid buffering

Estimation of Fuel Utilization During Exercise

- Indicates fuel utilization
  - 0.70 = 100% fat
  - 0.85 = 50% fat, 50% CHO
  - 1.00 = 100% CHO
- During steady-state exercise
  - VCO_2 and VO_2 reflective of O_2 consumption and CO_2 production at the cellular level

@ Rest

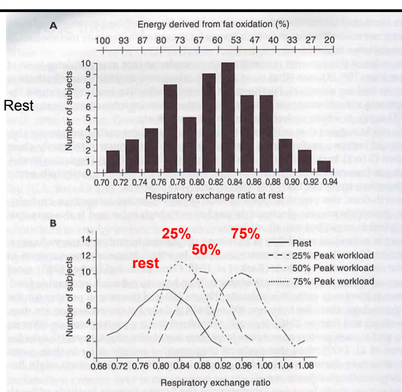
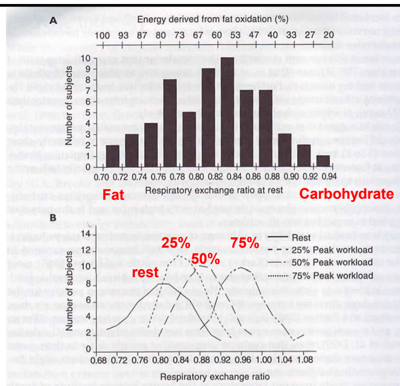


Figure 3.12 The distribution of the proportion of energy coming from fat oxidation in pers rest (A) and during exercise at 25%, 50%, and 70% of peak work rate (B).

From Goedecke, St. Clair Gibson, et al. (2000, p. E1328). © 2000 by The American Physiological Society. Adapt permission.



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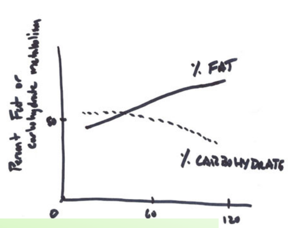
Variability

- Factors that influence variability in usage of fuel:
  - Muscle glycogen levels
  - Training volume
  - Proportion of Type I fibers
  - Resting blood free fatty acids
  - Lactate concentrations
  - Percentage of dietary fat intake
- Not all athletes are metabolically the same.

Duration of Exercise Influences Substrate Utilization

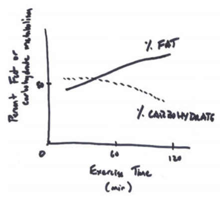


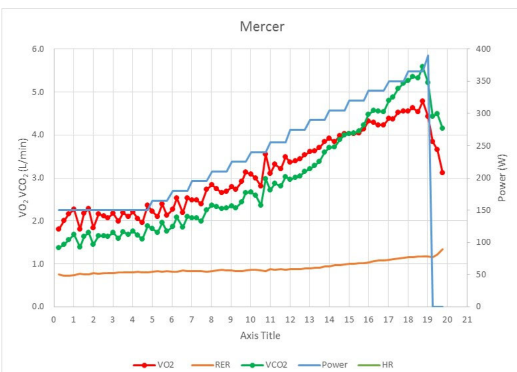
Costill (1970:
120 minutes of exercise @65% VO_{2max}

At start of exercise, 39% of energy came from fat.
At the end of exercise, 67% of energy came from fat.

Duration

- As duration increases, intensity is (often) lower.
- As duration increases, fat becomes an important fuel source.
  - The contribution of muscle glycogen reduces.
  - Liver glycogen (and hence blood glucose) also become depleted with duration.
- Practical point: It is important to take in carbohydrate during long durations.
- *Fat consumption?*





Factors affecting usage of food

- Fitness
  - Classic: Increased fitness reduces the amount of carbohydrate used during exercise.
  - Alternative:
    - Increased fitness leads to increase rates of fat oxidation at low intensities
    - Above 75% VO_{2max}, fitness leads to increased capacity to use blood glucose

Factors affecting usage of food

- Carbohydrate stores
  - There is a relationship between pre-exercise muscle glycogen concentrations and duration of exercise (~70% VO_{2max}).
    - Experimental limitation: Duration vs. distance
    - Is the cause of fatigue reduced muscle glycogen or something else?
      - Inc. body temp, SSC fatigue, liver glycogen, placebo?

Factors affecting usage of food

- What was last eaten and when?
  - Low levels of muscle glycogen levels are associated with fatigue.
  - Attempts have been made to understand how to preserve muscle glycogen.
    - e.g., Alter pre-race diet to increase reliance on fat metabolism.
      - It is not possible to increase fat metabolism by altering pre-race diet.
    - Carbohydrate ingested before exercise increases the amount of carbohydrate used during exercise.
      - Refueling during race is critical to preserving muscle glycogen (and liver glycogen) levels.

Factors affecting usage of food

- Ingesting Caffeine and Fat
  - Caffeine appears to have no metabolic value during exercise.
    - Possibly because caffeine loses its ability to mobilize fat when someone has carbo-loaded.
  - Caffeine does seem to enhance time to exhaustion.
    - Benefit could come as much as 4 hours after ingestion
    - ~ 3 mg/kg (a cup of coffee has about 40 – 100 mg)
      - 80 kg person would need about 3-6 cups of coffee
      - More than 9 mg/kg can increase negative side effects
    - Could be due to stimulatory effect vs. metabolism effect.
      - Supports the idea of Integrated Neuromuscular Recruitment Model.
    - Could be due to influence on muscle cell
      - Increase release of calcium?
  - Individual tolerance levels

Factors affecting usage of food

- Ingesting a High-Carbohydrate Meal
  - Eating a high-carb meal pre-exercise will increase the amount of carbs used during exercise.
    - Classic: Eating high-carb meal pre-exercise was not recommended because this might increase insulin levels.
      - Insulin is a hormone that controls the uptake of sugars, proteins and fats.
      - Insulin functions to lower blood glucose levels; therefore, one should not exercise with elevated insulin levels.
    - Contemporary: Not all carbohydrates are equal.
      - Carbs with high Glycemic Index (GI) cause a rapid rise in blood glucose concentrations. Release of insulin is stimulated.
      - Carbs with low GI cause a smaller, more delayed rise in blood glucose (and therefore less insulin response).
        - » Probably a good idea to have carbs with low vs. high GI pre-exercise.

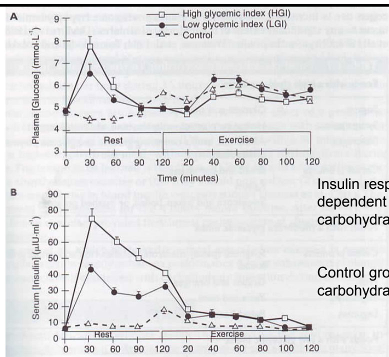


Figure 3.14 Plasma glucose (A) and serum insulin (B) concentrations 2 hours after ingestion of high and low glycemic index (HGI and LGI) carbohydrates at time 0, followed by 2 hours of exercise during which subjects ingested carbohydrates at regular intervals. In the control trial, subjects did not ingest carbohydrate before exercise.
From Burke, Classen, et al. (1998, p 2222). Copyright 1998 by the American Physiological Society.

Insulin response dependent on type of carbohydrate taken in.

Control group = no carbohydrate intake.

Table 3.2 Food classification according to the glycemic index

Foods with a high glycemic index	
Sugars	Glucose and sucrose
Syrups/jams	Honey, corn syrup, molasses, cane, and maple sugar
Beverages	All athletic drinks containing glucose and glucose polymers (maltodextrins)
Cereal products	Bread and cornflakes
Fruit	Raisins
Vegetables	Sweetcorn and baked, boiled, or mashed potatoes
Foods with a moderate glycemic index	
Cereal products	Spaghetti (pasta), macaroni, noodles, rice, and whole grain rye bread
Fruit	Grapes and oranges
Vegetables	Yams and corn
Legumes	Baked beans
Foods with a low glycemic index	
Fruits	Apples, cherries, dates, figs, grapefruit, peaches, pears, and plums
Legumes	Butter beans, kidney beans, chick peas (Garbanzo beans,) green beans, navy beans, red lentels
Dairy products	Milk and yogurt

Ingesting a High-Carbohydrate Meal

- Ingesting food 45 min – 4 hours before exercise might enhance performance.
  - There is a lot of variability in how people respond to eating pre-exercise and during exercise.
    - Practice nutrition plan
    - The effectiveness of the pre-exercise meal may be dependent on during-exercise use of carbs.
      - Prevent depletion of liver glycogen.

Factors affecting usage of food

- Nicotinic (Niacin) Acid Concentrations
  - B-group vitamin that inhibits fat mobilization.
  - Used to treat high-blood cholesterol.
  - Found in meat, whet germ, dairy products, and yeast
  - Inhibits fat mobilization
  - Minimal influence on performance
- Fasting Before Exercise
  - Fasting increases free fatty acid levels in blood.
  - However, performance is impaired due to hypoglycemia.

Factors affecting usage of food

- Taking in fuel during exercise
  - Glucose taken in during endurance exercise does not reduce overall rate of muscle glycogen use.
    - …but maybe reduced rate in Type I fibers
    - During intermittent high intensity exercise, glucose intake may spare muscle glycogen.
  - Glucose taken in during endurance exercise spares liver glycogen levels.
    - Ingested carbohydrate serves as a substitute for glucose released by the liver.

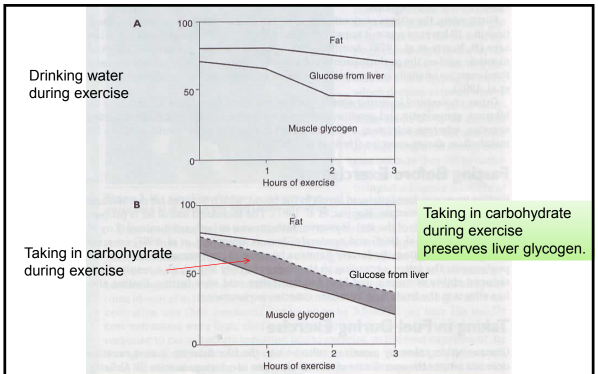


Figure 3.16 The percentage contribution to total energy expenditure from fat, blood glucose (from liver), and muscle glycogen during 3 hours of exercise at 70% $\dot{V}O_2$max when ingesting water (A) or carbohydrate (B). Ingested carbohydrate is used in preference to liver glucose. Hence, glucose ingestion during exercise spares liver but not muscle glycogen.
Data from Bosch et al. (1994).

Factors affecting usage of food

- The Athlete's Regular Diet
  - High-carbohydrate
    - Long thought to be necessary for optimal endurance performance.
    - Do athletes actually achieve high-carbohydrate diet?
      - McCowan & Edelstein, 2006; Hawley, et al. 1995
      - 3.15 g / kg vs. 6-10 g / kg BW [grams of carbohydrate per body weight]
  - High-fat
    - > 50% of daily calories from fat
    - Athletes may be able to adapt to this type of diet with no detrimental effects on performance.
    - …no convincing evidence that performance is enhanced.
    - Comparative nutrition: Endurance animals perform better on high-fat vs. high-carb diet.
  - Take home point: A variety of diets can be used that do not negatively influence performance.
    - …but, this must be a regular diet.

- Diet
  - Diet influences blood glucose levels during exercise

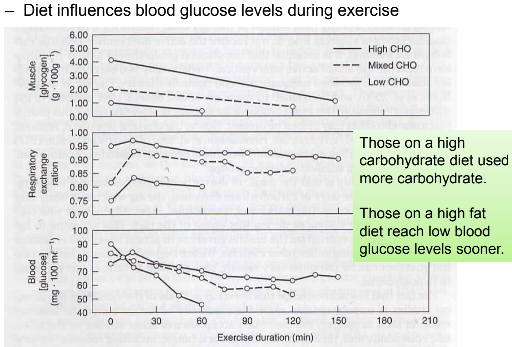


Figure 3.10 Hypoglycemia occurs rapidly in subjects eating a low-carbohydrate diet before exercise.
Data from Bergström, Hermansen, et al. (1967).

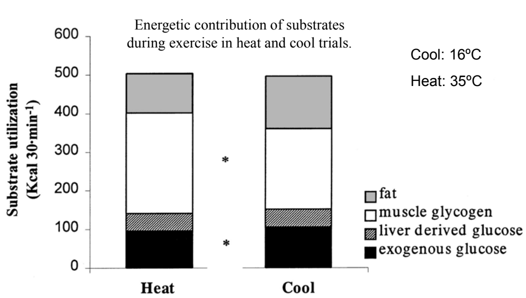
Factors affecting usage of food

- Gender
  - Women use more fat then men as a fuel during exercise intensities between 65% and 75% VO_{2max}.
    - …not always … trend
  - It is not clear if this offers an advantage.
  - During race carbo loading strategies should keep this in mind.

Factors affecting usage of food

- Environmental temperature
  - The rate of muscle glycogen use increases in the heat.
  - Carb ingestion aids performance but only when heat stress is managed.
  - Gastrointestinal problems increase with carb ingestion during heat.
    - Carb intake may need to be reduced in heat (50-60 g/hr vs. 60-70 g/hr).
- Ironman Louisville 2010

Jentjens, Wagenmakers, and Jeukendrup (2002). Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise. Journal of Applied Physiology, 92, 1562-1572.



Use of ingested carb decreased about 10% but the use of muscle glycogen increased 25% in heat vs. cool.

Factors affecting usage of food

- Warming Up
  - Warm up does not slow the rate of muscle glycogen use during exercise.
  - Warm up does increase blood flow to muscles and temperature of active muscles.
  - Not a factor influencing usage of food.

Increasing Carbohydrate Stores Before Exercise

- It makes sense to increase stores of carbohydrate pre-exercise.
  - …and to replenish during exercise
- Carbohydrate content of diet needs to be high
  - e.g., for a 70-kg runner, 600 g of carbohydrate per day.
    - 30 apples or 14 bagels or 11 potatoes
- Almost the same benefit can be achieved by ingesting carbohydrate pre-exercise.

Summary – Part 4

- Factors affecting usage of food
  - Intensity
  - Duration
  - Fitness
  - Diet
  - Carbohydrate stores
  - What was last eaten and when
  - Ingesting caffeine and fat
  - Ingesting a high-carb meal
  - Nicotinic acid concentrations
  - Fasting before exercise
  - Taking in fuel during exercise
  - The athlete’s regular diet
  - Gender
  - Environmental temperature
  - Warming up
  - Increasing carbohydrate stores before exercise

Part 5 – Maintaining fuel

- How to maintain Carbohydrate storage?

Central Governor's Role During Prolonged Exercise *(p144)*

- Why do athletes stop exercising?
- Remember … experimental models are either:
  - Time to exhaustion @some intensity
  - Time to complete distance
- Carbohydrate is stored in the muscle and liver. Blood glucose levels represent transport of carbohydrate from liver to muscle.
- Also … remember that some carbohydrate loading studies do or do not allow for carbohydrate intake during exercise.
- The bottom line of the next section is that endurance performance is enhanced by taking in carbohydrate during exercise at a rate of about 60 g / hr.

- Cyclist exercised as long as they could at fixed intensity ingesting either placebo or 100 g carbohydrate per hour.
- Ingesting carbohydrate during exercise prolonged time to exhaustion.
  - Blood glucose levels were maintained at exhaustion.
    - This means that exhaustion was not caused by low blood glucose levels.
  - Rate of carbohydrate oxidation and muscle glycogen concentrations remained unchanged.
    - Why did exhaustion occur at 4 hours instead of 3 hours when metabolic profile remained unchanged?

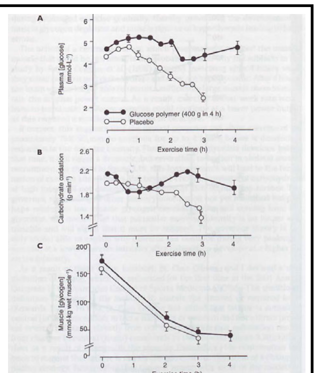


Figure 3.19 Effects of carbohydrate ingestion on plasma glucose levels (A) and on the rates of carbohydrate oxidation (B) and muscle glycogen concentrations (C) during prolonged exercise at 70% $\dot{V}O_2$max. Carbohydrate ingestion during exercise maintains blood glucose levels and rates of carbohydrate oxidation without affecting the rate of muscle glycogen use.

From Coyle, Coggan, et al. (1986, p. 167). © 1986 by the American Physiological Society. Adapted by permission.

Central Governor's Role During Prolonged Exercise

- Exhaustion is the point where work can no longer be accomplished.
  - Fatigue leads to exhaustion
  - Where did fatigue occur?
    - Constant work load
- Another experimental model is to have subjects complete a set distance as fast as possible.
  - Have subjects complete sprint trials at specific distance intervals.

- Task: Complete 100 K cycling time trial as fast as possible.
  - Sprint intervals completed along the way.
- Fatigue was apparent at the first 25 km sprint.
- EMG decreased across 100 K distance.
  - Evidence that the brain is recruiting less muscle?

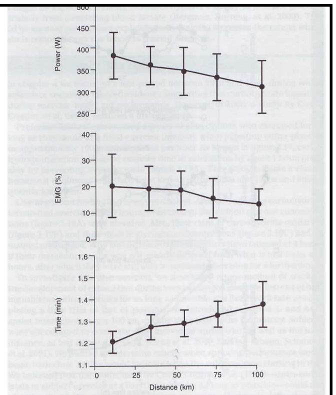


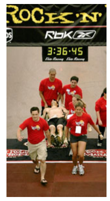
Figure 3.20 Power outputs, electromyographic activity (EMG), and time during consecutive 1-km sprints during a 100-km cycling time-trial in a laboratory.
Redrawn from St. Clair Gibson, Schabort, et al. (2001, R190). © 2001 by the American Physiological Society. Adapted by permission.

Central Governor's Role During Prolonged Exercise

- What is the significance of reduced muscle recruitment?
  - Prevent muscle glycogen depletion, muscle rigor, hyperthermia, heat-stroke, …?
- Examining Figure 3.19, maybe the central governor allows exercise of about 70% VO_{2max} to continue up to 4 hours before exercise intensity has to be decreased.
  - We don't know if subjects could have continued to exercise at a lower intensity.
  - However, if hypoglycemia develops, there is an earlier need to reduce muscle recruitment.

Fatigue

- General tiredness.
- Classic: Inability of muscle to sustain a desired or required force.
- Noakes: Physical manifestation of a change in pacing strategy.
  - Pacing is the key to success at endurance performance.
  - Fatigue and exhaustion are different concepts.
    - When one is fatigued, exercise can continue but at a lower intensity.
    - When one is exhausted, exercise cannot continue.
  - When pacing slows, maybe what is happening is the body is simply maintaining homeostasis.
    - Prevent rigor, myocardial ischemia, maintain body temperature, …
- "…sensory-cognitive syndrome which includes tiredness, …" Bartley, 1965.
  - …a perception of how much more work can be done.
- Exhaustion: No further work can be done.



Preventing Hypoglycemia

- Hypoglycemia (low levels of blood glucose) is preventable and reversible.
  - e.g., drinking a liter of coke (about 100 g carbohydrate)
- Hypoglycemia is more likely the longer the race.
  - 2% of runners in 42-km marathon
  - 6% @ 56 km
  - 11% @ 90 km
- At marathon pace (~85% VO_{2max}):
  - Muscle glycogen stores can last ~2 hours.
  - Liver glycogen stores can last ~2 – 2.5 hours.
- At ultramarathon pace (~70-75% VO_{2max}):
  - Muscle glycogen stores can last ~4-4.5 hours.
  - Liver glycogen stores used at about the same rate as marathon pace.
  - If carbs are not replaced during long duration races, hypoglycemia will result.

Carbohydrate Ingestion During Exercise

- Carbohydrate ingestion during prolonged exercise reduces the perception of fatigue while also delaying fatigue and increasing performance.
- Carbohydrate ingestion needs to occur throughout a race.
  - Carb ingestion near end of race not effective.
- Carbohydrate ingestion does not reduce the rate of muscle glycogen use but does protect liver glycogen stores.
- Carbohydrate ingestion is most important for endurance events > 2 hours.
  - However, maybe some positive influence at short (~1-hour), high intensity exercise.
  - But this is not due to prevention of hypoglycemia.

Type and Amount of Carbohydrate

- Most forms of carbohydrate are able to supply glucose to the bloodstream if ingested at rates of about 60 – 90 g per hour.
- Recommendations:
  - ~40-80 g per hour (typical target 60 g/hr)
    - Rate of use is ~1 g per min
  - Any palatable carbohydrate
    - Solid or liquid

Restocking Glycogen

- Eat high-carb diet post exercise
  - Do athletes really eat high-carb diet?
  - 8 g carbohydrate per kg body weight must be eaten daily (range: 6-10 g / kg).
    - 80 kg athlete » 640 g carbohydrate
      - 16 cans of coke
      - 30 apples
      - 10-20 bagels
    - Glycogen resynthesis not influenced by solid or liquid nature of carbohydrate.
    - Ingestion should begin immediately after exercise.
      - 50 – 80 g repeated 30-60 minutes and continuing for 5-6 hours.

Carbohydrate Ingestion During Exercise

Summary – Part 5

Part 6 – Lactic Acid

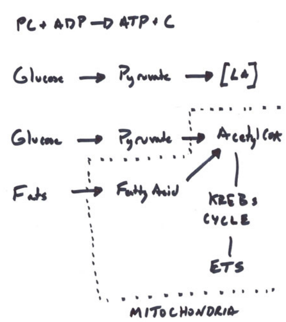
- In this next section, there is a focus on lactate production/removal during exercise.
  - Is lactic acid levels a cause of fatigue?
  - Are people stopping exercise because of lactic acid?
- The take home messages of this section are:
  - Distinguish between lactate threshold, OBLA, anaerobic threshold, ventilatory threshold, lactate turnpoint.
  - Understand Lactate Shuttle
    - Lactic acid may not be as bad as we once thought

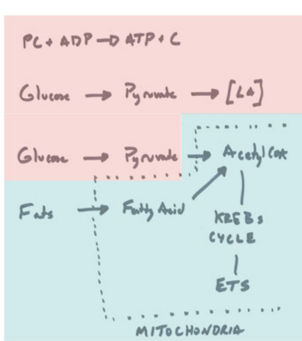
Energy Production During Supramaximal Exercise

- Supramaximal:
  - Intensities greater than 100% VO_{2max}.
  - 100 m sprint in 10 seconds
    - Average speed = 10 m/s = 22 mph
    - This would require 140 ml/kg/min
      - ACSM equation
      - VO_2 = 0.2*speed + 0.9*speed*grade + 3.5
      - VO_2 = 0.2*60 m/min + 0 + 3.5
      - VO_2 = 123.5 ml/kg/min
    - Either way, the VO_2 requirement is far greater than any VO_{2max} ever recorded.
      - Energy is transformed from chemical to mechanical from other oxygen-independent pathways.

Metabolic Pathways
…to produce ATP

- Anaerobic: without O_2
  - ATP-PC
  - Glycolysis
- Aerobic: with O_2





Anaerobic

Aerobic

Oxygen-Independent Metabolic Pathways

- ATP & PCr Stores
  - There is enough storage to support about 3-7 seconds of contractions.


Oxygen-Independent Metabolic Pathways

- Fate of glucose
  - Glucose broken down to ….
    - Pyruvate: Next stage is conversion to Acetyl-CoA
      - This happens in the mitochondria
    - Lactic Acid
      - This happens in sarcoplasm
  - The biochemical steps leading up to creation of pyruvate or lactic acid are the same.
    - Therefore, some references refer to 'aerobic' and 'anaerobic' glycolysis
  - Noakes emphasizes that 'glycolysis' refers to the production of ATP without O_2.
    - Oxygen-Independent Glycolysis
      - Lactic acid is end-point

Oxygen-Independent Glycolysis

- Technically, glycolysis is the hydrolysis of sugar (the steps leading up to pyruvate or lactic acid).
  - Pyruvate is transported into mitochondria and enters the Kreb's cycle.
    - Nicotinamide adenine dinucleotide (NAD) must be available to accept hydrogen ions.
  - If NAD is not available, pyruvate can accept hydrogen ions to form lactic acid
- Takes place in the sarcoplasm
- Requires some energy (i.e., energy investment) to yield energy.
- ATP is generated at a fast rate.

Lactate Metabolism

- Lactic Acid is an end point of glycolysis.
- At normal body pH (~7.35), lactic acid will rapidly dissociate to form lactate.
- Therefore, the terms lactate and lactic acid are commonly used interchangeably.
  - Lactic acid is unstable and is rapidly converted to lactate.

Lactate Metabolism

- Muscles produce and use lactate.
- Rate of production increases with exercise intensity.
- Classic view: Lactic acid was associate with fatigue, cramps, side-stitch, post-exercise muscle soreness.
  - Proteins denaturize in acidic environments.
- Contemporary: Lactic acid is a fuel.

Lactate Threshold

- The point during a graded exercise test where there is a systematic increase in lactic acid concentration.
  - The basic concept is that this point signifies when ATP is being generated to a greater extent anaerobically vs. aerobically.
  - Therefore, this point is also known as:
    - Anaerobic Threshold
    - Ventilatory Threshold
      - This is actually a little different. This threshold coincides with the point where there is a systematic increase in exhaled CO_2.
      - This could coincide with the lactic acid (e.g., buffering mechanism).
    - Onset of Blood Lactate Accumulation (OBLA) does not coincide with any of these points. This parameter represents the point where lactic acid concentrations have exceeded some predetermined levels (e.g., 4 mmol).

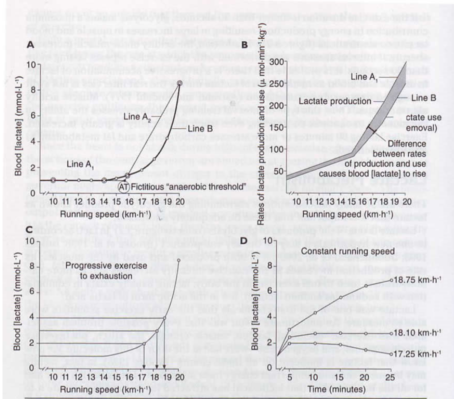
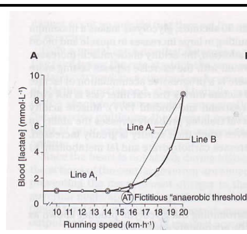


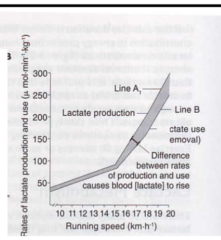
Figure 3.22 Blood lactate concentrations rise as an exponential function of running speed.



- At low running speeds, lactic acid levels remain low.
  - Evidence suggests that ATP is being produced aerobically.
- At faster running speeds, lactic acid levels increase.
  - Classic: muscles became progressively more anaerobic (i.e., more [La] produced).
    - The point of increase is not always easy to identify and is debatable.
  - Contemporary: [La] is a result of production and use (Fig 3.22 B).

Figure 3.22 Blood lactate concentrations rise as an exponential function of running speed.

- Lactic acid is used by muscles (the ones producing as well as others), the heart and liver.
- Lactic acid levels are a result of the difference between production and use.
  - The presence of lactic acid in the blood is thought to be a mechanism to prevent acidic conditions within the muscle cell.
- There is not necessarily a clearly defined threshold of increase in [La].



Blood lactic acid concentration =
lactic acid entry into blood – blood lactic acid removal

Figure 3.22 Blood lactate concentrations rise as an exponential function of running speed.

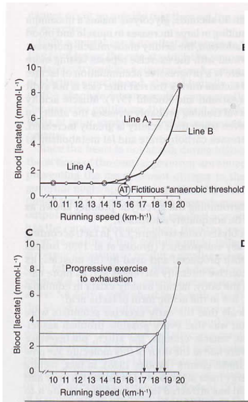


Figure 3.22 Blood lactate concentrations rise as an exponential function of running speed.

- Another method for looking at the levels of lactic acid is identifying the speed (or intensity) at which a specific level of concentration is reached
  - e.g.: 2, 3, or 4 mmol/L
- This corresponds to the OBLA concept.

- Lactic acid levels while running at a constant speed.

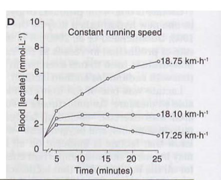


Figure 3.22 Blood lactate concentrations rise as an exponential function of running speed.

Lactate Metabolism

- Lactic acid levels increase with intensity.
- Noakes uses the term 'Lactate Turnpoint' to represent the exercise intensity at which blood lactate concentrations begin to rise visibly.
  - However, he is careful to note that no threshold exists even though identifying a lactate turnpoint suggest there is a threshold.
  - Lactate levels are a function of production and use.

Biochemical Explanations for Increased Lactate

- At high intensities, carbohydrate is the main fuel.
- Glucose is oxidized to pyruvate if NAD is available.
  - If NAD is not available, lactate is produced.
  - Lactate is transported out of the muscle cell.
    - To prevent acidic build up in muscle cell?
    - If so, then lactate is benefitting performance.

Lactate Turnpoint

- The exercise intensity (i.e., running speed) associated with the point where lactate begins to rise visually may be a good predictor of performance.
  - Training has the effect of shifting the lactate turnpoint to a higher running speed.
- Determining the lactate turnpoint is time-consuming.
  - It may not offer any increased predictability compared to velocity at VO_{2max}.

Lactate Shuttle

- Brooks:
  - Lactate is an important metabolic fuel.
  - Active muscles produce and use lacate at rest and during exercise.
  - Lactate that is produced as an end-product of glycolysis is
    - transported into mitochrondria oxidized via Krebs cycle
    - Released into the blood stream where it can be used by other muscles (e.g., heart, other muscles)
    - Released into the blood stream where it can be used by the liver (production of blood glucose).
- The lactate turnpoint represents the point where production of lactate exceeds use of lactate.
- The Lactate Shuttle represents the movement of lactate away from active muscles.
  - Does this represent a mechanism of transport of fuel between cells?

Lactate and Exhaustion

- If lactate is infused into the bloodstream, it has no noticeable effects.
  – It is important to prevent build up of hydrogen ions (and formation of lactate helps prevent this).
- Lactate levels are not necessarily high after prolonged exercise (e.g., marathon).

Lactate Removal after Exercise

- Is lactate a cause of muscle soreness?
- Lactate levels can return to normal levels within an hour post-exercise.
- Muscle soreness can occur after long races in which the intensity is below the lactate turnpoint.
  – Lactate levels are not high.
- Sprinters are not always sore.
  – Lactate levels can be high.

Summary – Part 6

- Lactate turnpoint: point at which [La] starts to increase.
  – Lactate threshold, OBLA
- Blood lactic acid levels are a result of the amount of [La] produced and the amount used.
  – Lactate Shuttle

Part 7 – Training responses

- What metabolic changes are there in response to training?

Metabolic Adaptations to Training

- Main metabolic adaptations:
  - Increased VO_{2max}.
  - Increased capacity to store muscle and liver glycogen.
  - Increased use of fat as fuel.
  - A shift in the lactate turnpoint to a higher running speed.
- Causes?

Metabolic Adaptations to Training

- Increased capillarization
  - The number of blood capillaries surrounding muscle fibers increase with training.
    - Facilitates transport of oxygen and fuel to muscle.
- Glycolytic pathway adaptations
  - Sprint training leads to increase of certain glycolytic enzymes & ability to tolerate high levels of acidity (better buffering capabilities?).

Metabolic Adaptations to Training

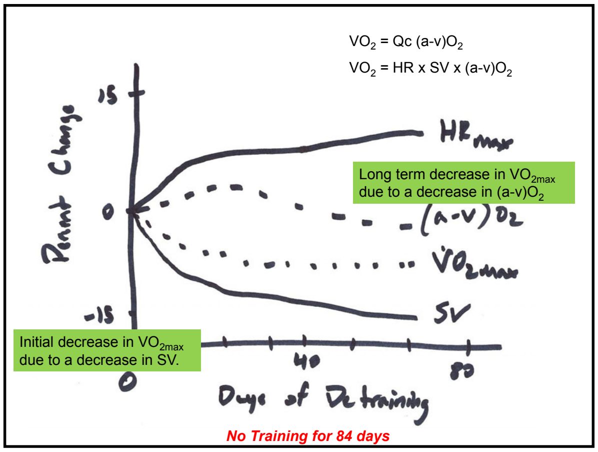
- Changes in the mitochondria
  - Increases in number and size.
  - Increase ability to oxidize fat.
    - Leads to a reduce level of lactate production (at low levels of intensity).
      - Causes a shift of the lactate turnpoint to faster speeds.
- Changes in muscle contractility
  - Does training change the ability of muscle to generate force?
    - Increased myosin ATPase activity?
    - Enhanced calcium handling?
- Increased capacity to recruit muscle mass
  - Neuromuscular Recruitment Model: increased ability of brain to recruit muscles (e.g., coordination, effectiveness).
    - Short-term training benefits are not from metabolic changes.

Effects of Training and Detraining

- The effect of training can be seen quickly.
  - VO_{2max} can be increased within a week of intensive training.
    - To sustain improvements, training frequency, intensity and duration need to be manipulated to increase training volume and intensity.
  - VO_{2max} can decrease quickly with detraining.
    - Detraining and Tapering are different concepts

Fick Equation

- $VO_2 = Q_c(a\text{-}v)O_2$
  - Q_c = HR x SV
    - HR: Heart rate
    - SV: Stroke volume; amount of blood ejected with each beat
  - $(a\text{-}v)O_2$: Difference in the amount of oxygen in arterial and venous blood
    - Represents how much oxygen was extracted from the blood
- $VO_2 = HR \times SV(a\text{-}v)O_2$



Preventing Detraining

- What is the minimal amount of training needed to sustain or maintain fitness and/or performance?
  - Reducing training volume by up to 70% for 3 weeks did not negatively impact performance (e.g., Houmard, Costill, et al., 1990).
  - The 'art' of designing a training program … how to avoid detraining while maintaining performance and reducing risk of injury?

Heredity Capacity to Adapt to Endurance Training

- Is there a specific gene that leads to superior endurance ability?
- Some sedentary people have high VO_{2max} values (Powers, p 266).
- …pick your parents wisely ….

Summary – Part 7

- Training
  - Metabolic changes
    - Increased glycolytic enzymes, mitochondria (size and number of), number of capillaries, neuromuscular recruitment.
- Detraining
  - Decrease VO_{2max}, SV, (a-v O_{2diff})