ENERGY UTILIZATION DURING ENDURANCE EVENTS
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Adapted from: *Energy utilization* presentation by Dr. Johan P Kotze (PVM Scientific Advisory Board)

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1. BACKGROUND TO METABOLISM
ENERGY AND METABOLISM

All the processes of LIFE depend on energy input. Energy powers the biochemical reactions of life processes. For most people energy is a vague and enigmatic entity. In a broad sense the word METABOLISM refers to the cyclic flow of energy. Metabolism describes the reaction path(s) through which energy flows in the human body in order to sustain life. On a macro level it is the process of ingestion, digestion and absorption of energy through food. On a micro level it is the flow of energy through the cellular metabolic pathways (glycolyses, the Krebs-cycle and oxidative phosphorylation).

MACRO-NUTRIENTS

Light energy from the sun becomes trapped in plants as carbohydrates by photosynthesis. Via a food-cycle this energy is transferred to animals (which eat plants) and humans may then ingest carbohydrates directly from plants or fats and proteins from animal sources (macro-to-micro energy cycling).

Macro-nutrients are:

- Carbohydrates
- Fats
- Proteins

ANABOLISM AND CATABOLISM

Energy is cycled between anabolic (structural) and catabolic (functional) biochemical reactions. Both sustain life. Catabolically liberated energy can power the processes and functions needed to perform physical activity or exercise (work).
As the macro-nutrients flow through the metabolic pathways they are degraded into smaller molecules and energy is partially liberated along the way by this graded disintegration of the macro-nutrients. This is termed substrate-level phosphorylation because O_2 is not consumed. The energy-cycle of metabolism ultimately leads to cellular respiration. Respiration is the cellular consumption of O_2 for nutrient combustion. At the finish line trapped energy is released as ATP. The nutrient has been fully degraded and finally burned in the presence of O_2. CO_2 and H_2O (a gas and a liquid) is set free and some energy is inevitably lost as heat. This takes place within the mitochondria, cellular power-plants. This final process is oxidative phosphorylation because O_2 is consumed. The liberated ATP is immediately coupled or channelled into life-sustaining reactions like performing work via contracting muscles or repairing structures like damaged muscle.
The energy cycle continues.

- **The energy released from oxidation of the macro-nutrients are:**

Carbohydrates	:	4,2kcal/g (17,5kJ/g)
Fats	:	9,45kcal/g (39,5kJ/g)
Protein	:	5,65kcal/g (23,6kJ/g)

- **Because of incomplete metabolism in the body the available energies are:**

Carbohydrate	:	4,0kcal/g (17kJ/g)
Fats	:	9,0kcal/g (39kJ/g)
Proteins	:	4,0kcal/g (17kJ/g)

STORING ENERGY

The macro-molecule protein is stored within structures such as muscle in the human body. Muscles serve a functional role and the protein within muscle is not ordinarily made available as an energy source. A significant amount of fat can be stored within specialized cells termed adipose tissue. This emphasizes the important role of fat as a main source of energy under resting metabolic conditions. It is clear that carbohydrate stored as glycogen within muscle and liver is a significant energy source for the human body under high demand conditions. The metabolic demand which enables the human body to perform physical work on the environment is highly dependent on the flow of carbohydrate through the energy-transformative metabolic paths. Physical transformation processes of the human body on the world or on itself (physical exercise, activity and sport) WILL require carbohydrate input. Without carbohydrates transformation is not possible.

In short:

- the body does not store
- protein, but can store
- carbohydrate as glycogen in the muscles and liver,
- fat in adipose tissue
- 1g of glycogen is stored with about 2,7-2,8g water (26%)
- 1g fat is stored with about 0,25g water (80%)
- Fat is a more energy dense store than glycogen

ENERGY CURRENCY – ATP

The whole metabolic system is designed to degrade the macro-nutrients to ATP (adenosine triphosphate). All the pathways degrade in the direction of oxidative phosphorylation, the peak or point of MAXIMUM energy liberation. The different paths of carbohydrate, protein and fat metabolism are channeled and narrowed and all converge upon the common Krebs-cycle. Separate metabolic paths are like small rivers that converge in a dam, from where the flow is directed in a single current or path towards a single endpoint. The Krebs-cycle is an important regulation/integration point in metabolic energy flow, as a dam with gates is a regulation point in the flow of water. Regulation is accomplished with enzymes in the Krebs-cycle or gates in the case of a dam-wall. At the endpoint ATP is released. This is THE COMMON metabolic energy molecule or free-energy currency. It powers all reactions.

ENERGY PATHWAYS OR SYSTEMS

- When 1 mol of glucose is used by glycolysis, (180g) 2 mols of ATP are generated (without oxygen). [1:2]
- Glucose + 2ADP + $2P_i \rightarrow$ 2L (+) lactate + 2ATP + $2H_2O$
- The glycolytic route can function at a rapid rate delivering 3 times as much ATP in a given time period than oxidative phosphorylation lasting for 7s–1min. (Mougois 2006).
- Under aerobic conditions (with O_2) (glycolysis + Krebs-cycle + mitochondrial oxidative phosphorylation) 1 mol of glucose yields 38mol ATP. [1:38]

- With an energy yield of 12,3kcal/mol it is a 68% energy yield. 32% is lost as heat.
- (Older calculations used a 7,3kcal mol yield for ATP≈≈40% yield) (Murray et al 2000)
- When fat is used 129mol ATP is produced per mol palmitate. Also at 68% efficacy.

2. METABOLIC REGULATION DURING EXERCISE

INTENSITY

The choice of nutrient and regulation of metabolism (which portions of the path will dominate: glycolyses vs. oxidative phosphorylation or carbohydrate-to-fat ratio) is determined mainly by the intensity of the activity, but other factors such as genetic ability may also play a role. Intensity is the energetic-metabolic demand of the task. It was demonstrated above that maximal ATP-release is a combustion reaction with O_2. O_2 intake is eventually linked and translated to ATP-energy release. VO_2max is the maximum volume of oxygen inspired with maximal exercise efforts.

With high intensity activities (>80% VO_2max) carbohydrate (glycogen) is used for energy. The glycolytic pathway dominates. Glycolyses is the carbohydrate-path which leads the way to the Krebs-cycle by the formation of pyruvate. It can provide 'fast' energy (2 ATP's per glucose) because its enzymes can function at a high rate. When the path is over-taxed by demand, the rate of the enzyme-carrier pyruvate-dehydrogenase (PDH) is exceeded and it cannot transfer enough pyruvate to the Krebs-cycle to proceed to oxidation. This gate has a functional limit and if pyruvate levels increase it will by product-inhibition "brake" glycolyses. The pyruvate that cannot enter the gate is diverted along the only other available alternative route towards lactate formation. The shunting of pyruvate to lactate is a sink which allows glycolyses to continue at a high rate for a certain time-period at a high intensity. High intensity cannot be maintained indefinitely. The mechanisms and reasons of fatigue are not fully understood. The higher the intensity, the higher the glycogen-usage and the more lactate accumulates in a shorter time-period. Lactate is a carbohydrate fuel source for muscle, the brain and the heart when it becomes available during high glycolytic activity.

The end-point of lipid metabolism also converges on the PDH-enzyme or gate of the Krebs-cycle. The Krebs-cycle is the common bridge leading to oxidative phosphorylation. At lower intensities (<75% VO_2max) the glycolytic capacity (PDH-enzyme's functional rate) is not exceeded. Fat metabolism is able to contribute and sustain the energetic demand of the activity. This is the case during endurance. The higher the intensity, proportionally more glycogen is used instead of fat. At lower intensities of longer duration fat is preferred.

3. METABOLIC DEMAND OF RUNNING

NUMBERS AND FIGURES:

80-100g of ATP is initially 'stored' within the intracellular nucleotide-pool. During maximal bursts or explosive efforts it can be regenerated by the phosphagen system (creatine-phosphate) lasting for about 5-10 seconds. When glycolytic metabolism proceeds to the Krebs-cycle and mitochondrial oxidation the net reaction can be simplified as:

Carbohydrate → $CO_2 + H_2O$

Glycogen Body Stores

400g in muscles + 100g in liver + 20g in blood = 520g
A total of 500-550g is stored under normal conditions.
Glycogen + stored water = 2050g (Extra weight – Muscles feel "full" or "stiff")
Resting Metabolic Rate (RMR) = 1760 kcal/day (70kg person) (McArdle et al 2001)

For Comrades Marathon (flat surface level conditions)

Needed 70kg X 90km = 6300kcal
RMR for 6 hrs = 440kcal
= 6740kcal
1kcal/kg/km for level running NB!

To finish the Comrades Marathon in 6 hours (70kg)

- Average speed is 15km/hr
- Average energy expenditure 18,7kcal/min (19kcal)

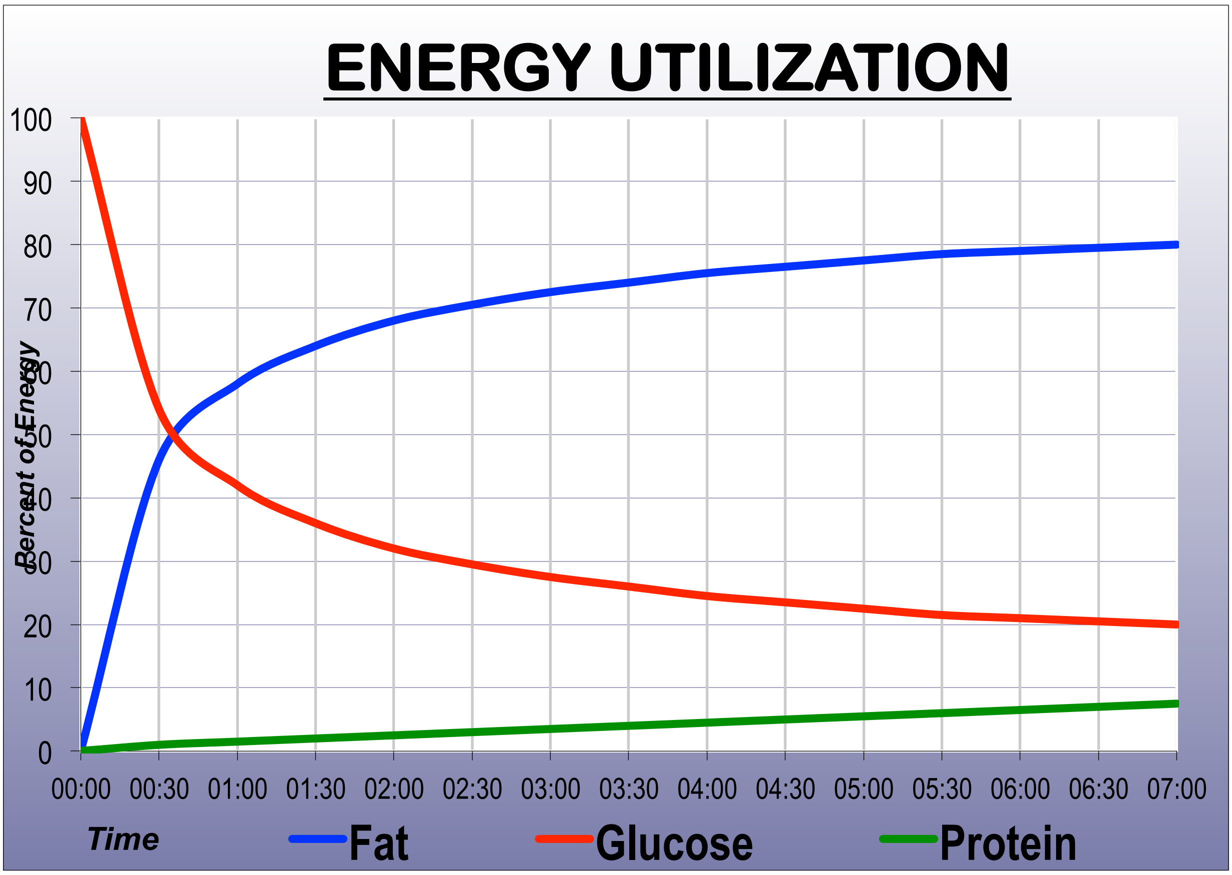
1117 kcal/hr (1120kcal/hr)
This means 4,7g glucose/min
520 = 111 minutes
4,7
The stored glycogen will last 110min or 1hr 50min
With glucose intake of 1g/min (60g/hr) max for the whole race another 77min can be added to the 111 **= 188 min.** (***Just over 3 hrs.***)

Normally a runner would not take in energy drinks before 30-60min into the race. (*18,7min*)
Thus, the stored glycogen plus extra intake will supply energy for about *170min*.
Other energy sources will be required (*3hr10min*)!

- **PROTEIN:** The body can and does use some protein for gluco-neogenesis (converting protein to glycogen/glucose). Normally at the end of the race the energy obtained from protein is 7-10% of the usage/min.

- **FAT:** The rest (>50%) is derived from stored FAT (3550kcal). 395g fat is oxidized.

Figure 1: % energy from macronutrients during an endurance race



- **Fat** supplies between 50-60% of the energy of a Comrades Marathon. Athletes store 7-12kg fat (395g ≈≈500g adipose tissue!).
- **The brain** uses 90±5% ***glucose*** for energy under ideal circumstances. At higher intensities the brain can utilize glycolytically produced ***lactate*** as a source of energy (Schurr & Payne 2007). Lactate is distributed by what is known as the Lactate-shuttle (Hashimoto & Brooks 2008).
- **Heart muscle** uses 90±5% ***fat*** for energy ($3X10^9$ beats/lifetime) but under high intensity demands will make use of ***lactate*** as a fuel (Hashimoto & Brooks 2008). Heart muscle at rest utilizes about 12% of the total metabolically produced energy. During exercise this can more than double (Ganong 1999).
- Training and nutritional strategies can improve the body's ability to store and utilize fat more efficiently (Van Hall et al 2000). Training and nutritional strategies lead to metabolic adaptations enabling the body to use fat at higher intensities of % VO_2max.

4. METABOLIC DEMAND OF CYCLING
DATA

Table: Energy needed per kilogram bodyweight per kilometer

	MOUNTAIN BIKING	ROAD CYCLING	ROLLER BLADING	SWIMMING	RUNNING
Energy Expended kcal/km/kg	0.80 (0.61-0.90) (3.34kJ)	0.50 (0.43-0.60) (2.09kJ)	0.50 (0.42-0.53) (2.09kJ)	3.5 (3.1-4.0) (14.63kJ)	1.00 (0.86-1.15) (4.18kJ)

Data calculated from 1. (Colombani et al 2002), 2. (Saris et al 1989), 3. (Padilla et al 2000), 4. (Kotze F, Personal Communication 2003).

- These data provide us with new insights into energy needs of different sports
- The lower energy needs for exercise on wheels are because the feet do not carry the weight, (biking, roller-blading). Cyclists do not use their upper body as much as is the case during running or walking.
- The higher energy need for swimming is because of water drag.
- Performing work of the same intensity (of any activity i.e. cycling vs. running) will require the same amount of total energy usage. Because the specific demands of the activities (i.e. upper vs. lower body muscle mass involved) differ, the VO_2max achieved at maximum effort will differ. With running a higher VO_2max is achievable because a greater muscle mass is involved. Proportionally more fat-to-carbohydrate is used during running than cycling. 30% more fat is used for running when compared to cycling. The intensity at which maximal fat oxidation occurs is not different between running and cycling. (Van Achten et al 2003)
- Fat is the predominant fuel source at intensities of 55-80% of VO_2max.
- Cyclists use more carbohydrates and runners use more fat.

BLOOD SUGAR

Stable blood glucose is important to sustain energy levels. If blood glucose falls under 3,8mmol/L a glucagon, epinephrine and growth hormone response is activated and at 3,2mmol/L cortisol is released (a stress hormone) and at 2,8mmol/L cognitive dysfunction can occur. Glucose should be between 4,5 and 6,4mmol/L for individuals at rest. On the other hand too high blood glucose inhibits fat utilization. During strenuous activity blood glucose can increase and peak at levels around 11mmol/L before returning to lower levels via regulatory mechanisms.

SUMMARY

- Energy is released from macronutrients by metabolic processes.
- Glycolysis produces ‘fast’ energy (2ATP/mol glucose) at high intensities and lactate accumulates. Lactate formation is a sink and lactate is a carbohydrate fuel.
- Oxidative aerobic exercise at lower intensities (VO_2 max) produces much more usable energy - 38ATP/mol glucose.
- Fat as an energy source produces 129 ATP/mol from palmitate.
- The brain needs carbohydrates as energy source (90±5%). During rest the preferred source is glucose, but when lactate is available it can and will be used as a fuel.
- Heart muscle uses fat as an energy source (90±5%) under resting conditions but can also use lactate when it is available under high intensity conditions.
- Endurance exercise starts with mainly carbohydrate usage (glycogen stores) for energy but gradually switches over to fat usage within 30-60min.
- Running demands more fat usage and cycling uses more carbohydrates.
- Specific energy demand for 5 sports are (kcal/kg/km) Mountain biking 0,8; Road cycling 0,5; Roller-blading 0,5; Swimming 3,5; Running 1,0.

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