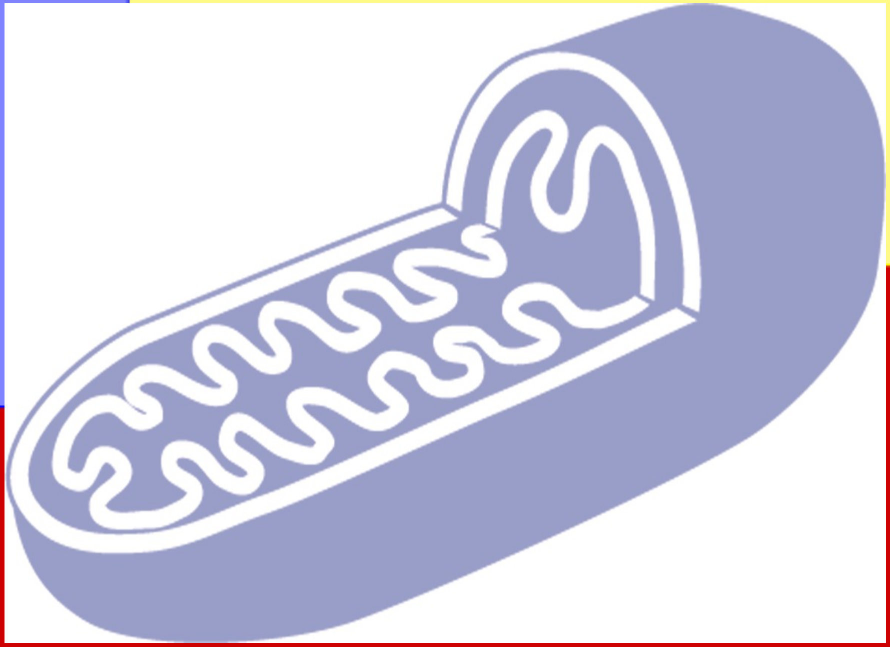
METABOLISM, ENERGY, AND THE BASIC ENERGY SYSTEMS



Learning Objectives

- Learn how our bodies change the food we eat into ATP to provide our muscles with the energy they need to move.
- Examine three systems that generate energy for muscles.
- Explore how energy production and availability can limit performance.

(continued)

Learning Objectives

- Learn how exercise affects metabolism and how metabolism can be monitored to determine energy expenditure.
- Discover the underlying causes and sites of fatigue in muscles.

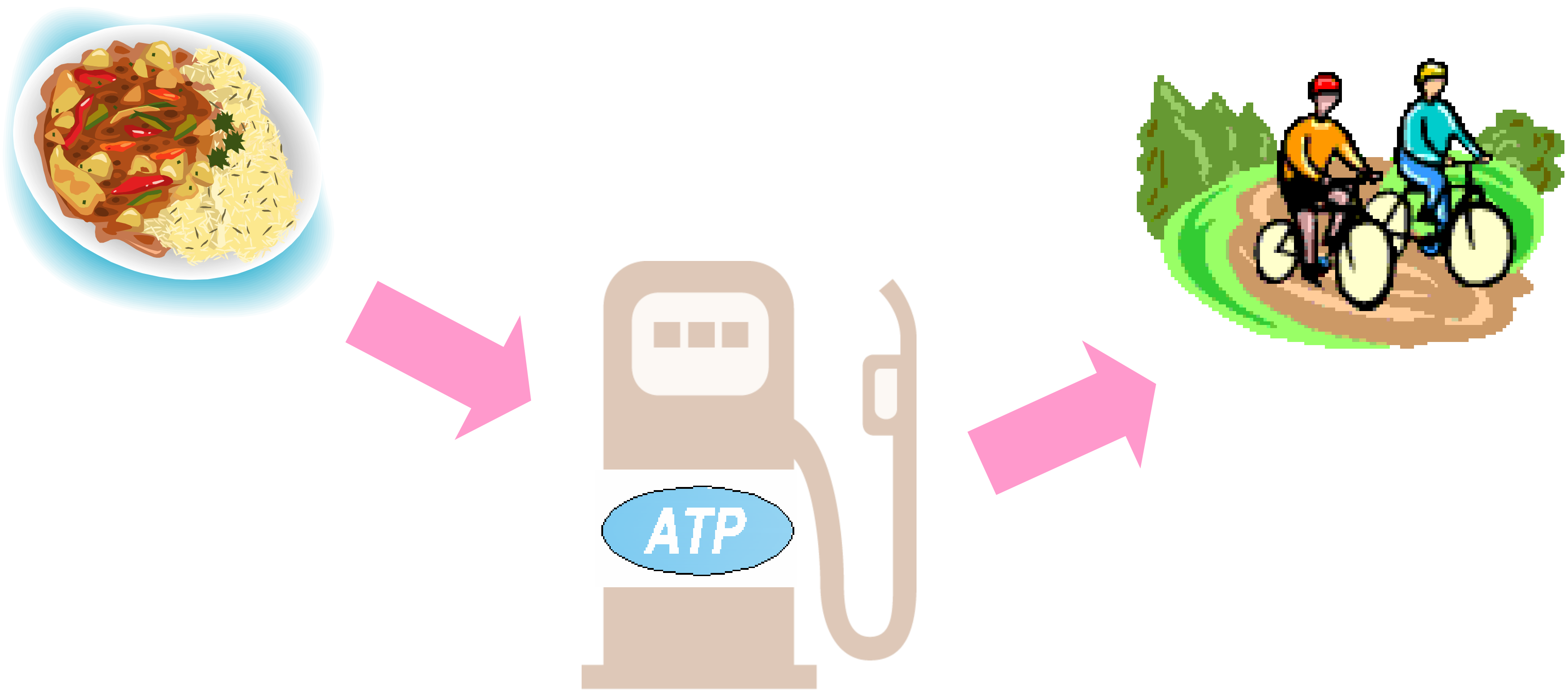
Calorie and Kilocalorie

- Energy in biological systems is measured in calories (cal).
- 1 cal is the amount of heat energy needed to raise 1 g of water 1°C from 14.5°C to 15.5°C.
- In humans, energy is expressed in kilocalories (kcal), where 1 kcal equals 1,000 cal.
- People often mistakenly say “calories” when they mean more accurately kilocalories. When we speak of someone expending 3,000 cal per day, we really mean that person is expending 3,000 kcal per day.

Energy for Cellular Activity

- Food sources are processed via catabolism—the process of “breaking down.”
- Energy is transferred from food sources to our cells to be stored as ATP.
- ATP is a high-energy compound stored in our cells and is the source of all energy used at rest and during exercise.

Energy for muscles



Energy Sources

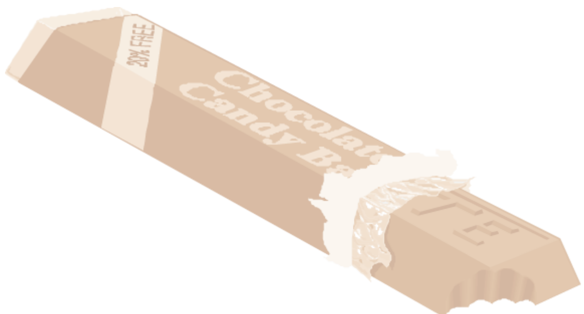
- At rest, the body uses carbohydrates and fats for energy.
- Protein provides little energy for cellular activity, but serves as building blocks for the body's tissues.
- During moderate to severe muscular effort, the body relies mostly on carbohydrate for fuel.

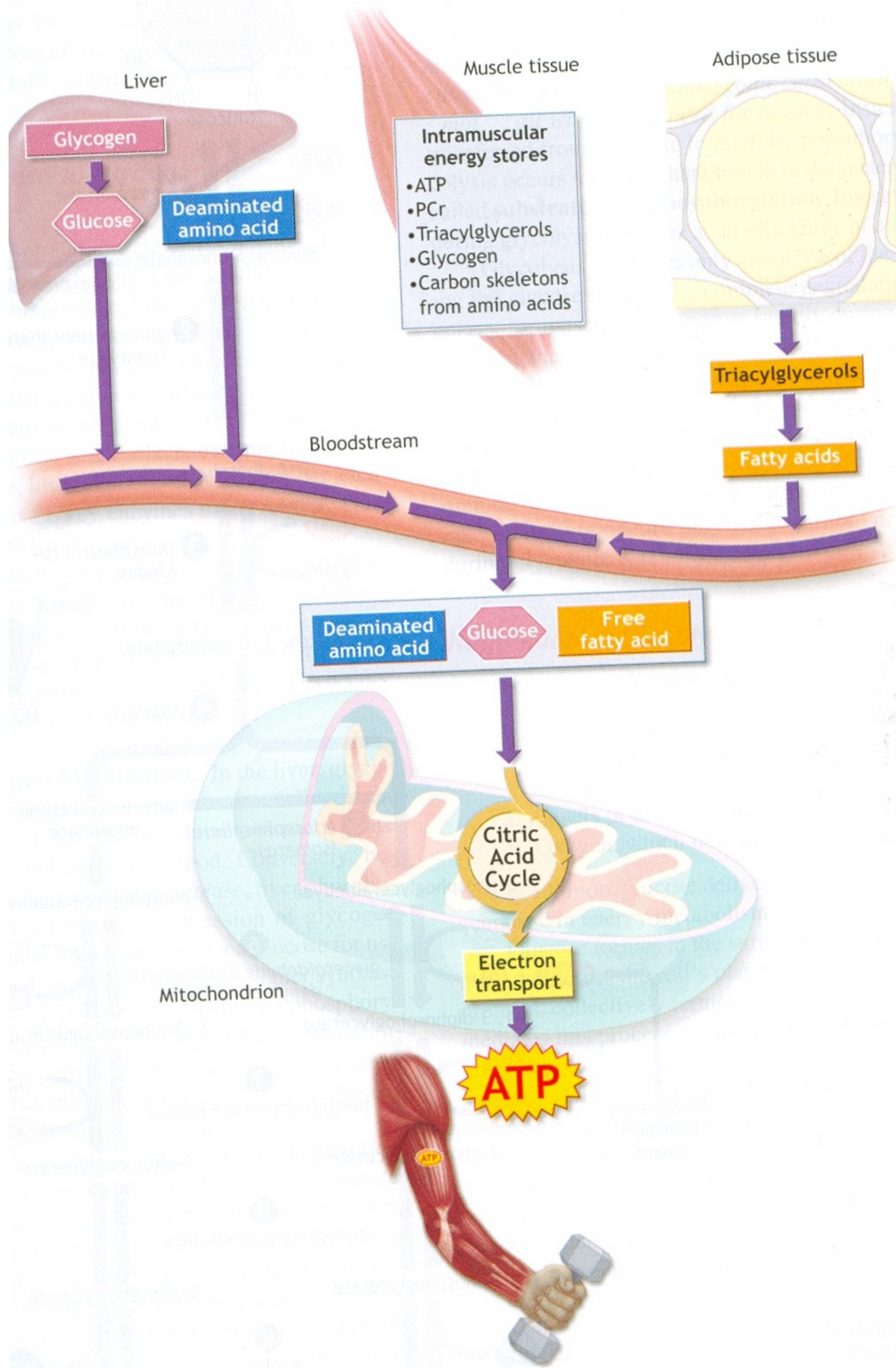
Carbohydrate

- Readily available (if included in diet) and easily metabolized by muscles
- Once ingested, it is transported as glucose and taken up by muscles and liver and converted to glycogen
- Glycogen stored in the liver is converted back to glucose as needed and transported by the blood to the muscles where it is used to form ATP
- Glycogen stores are limited, which can affect performance

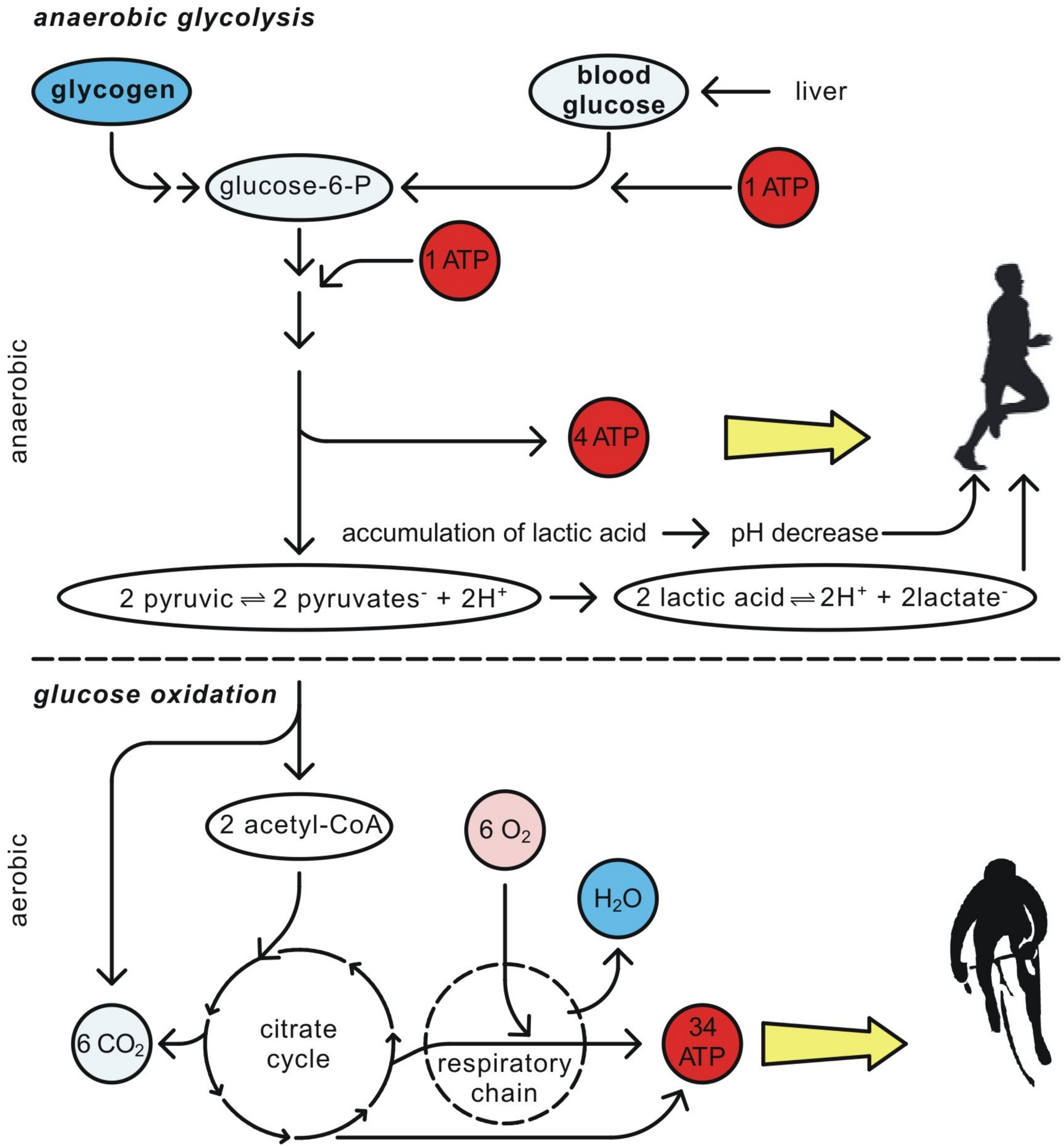
Fat

- Provides substantial energy at rest and during prolonged, low-intensity activity
- Body stores of fat are larger than carbohydrate reserves
- Less accessible for metabolism because it must be reduced to glycerol and free fatty acids (FFA)
- Only FFAs are used to form ATP
- Fat is limited as an energy source by its rate of energy release





Liver
Glycogen
Glucose
Deaminated amino acid
Muscle tissue
Intramuscular energy stores
•ATP
•PCr
•Triacylglycerols
•Glycogen
•Carbon skeletons from amino acids
Adipose tissue
Triacylglycerols
Fatty acids
Bloodstream
Deaminated amino acid
Glucose
Free fatty acid
Citric Acid Cycle
Electron transport
Mitochondrion
ATP



anaerobic glycolysis
glycogen
blood glucose
liver
glucose-6-P
1 ATP
1 ATP
anaerobic
4 ATP
accumulation of lactic acid
pH decrease
2 pyruvic ⇌ 2 pyruvates⁻ + 2H⁺
2 lactic acid ⇌ 2H⁺ + 2lactate⁻
glucose oxidation
aerobic
2 acetyl-CoA
6 O2
H2O
6 CO2
citrate cycle
respiratory chain
34 ATP

Body Stores of Fuels and Energy

	g	kcal
Carbohydrates		
Liver glycogen	110	451
Muscle glycogen	500	2,050
Glucose in body fluids	15	62
Total	**625**	**2,563**
Fat		
Subcutaneous and visceral	7,800	73,320
Intramuscular	161	1,513
Total	**7,961**	**74,833**

Note. These estimates are based on an average body weight of 65 kg with 12% body fat.

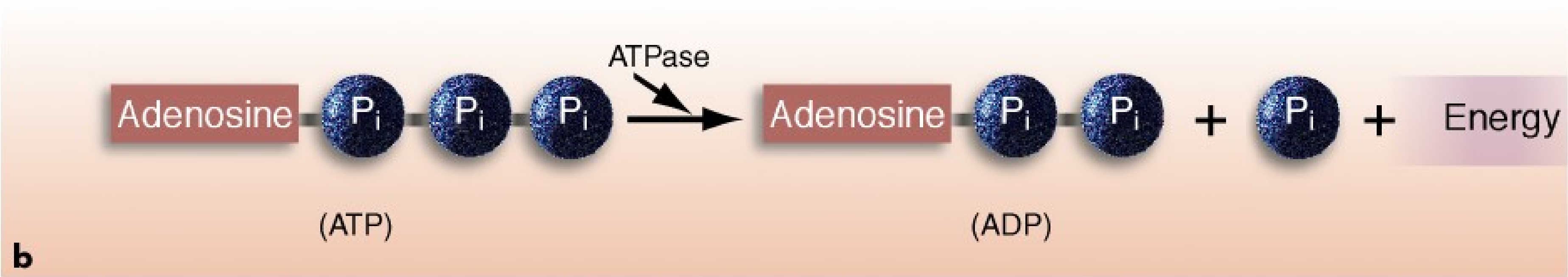
Protein

- Can be used as an energy source if converted to glucose via **gluconeogenesis**
- Can generate FFAs in times of starvation through **lipogenesis**
- Only basic units of protein—amino acids—can be used for energy: ~4.1 kcal of energy per g of protein

Basic Energy Systems

1. ATP-PCr system (phosphagen system)—cytoplasm
2. Glycolytic system—cytoplasm
3. Oxidative system—mitochondria or powerhouses of cell

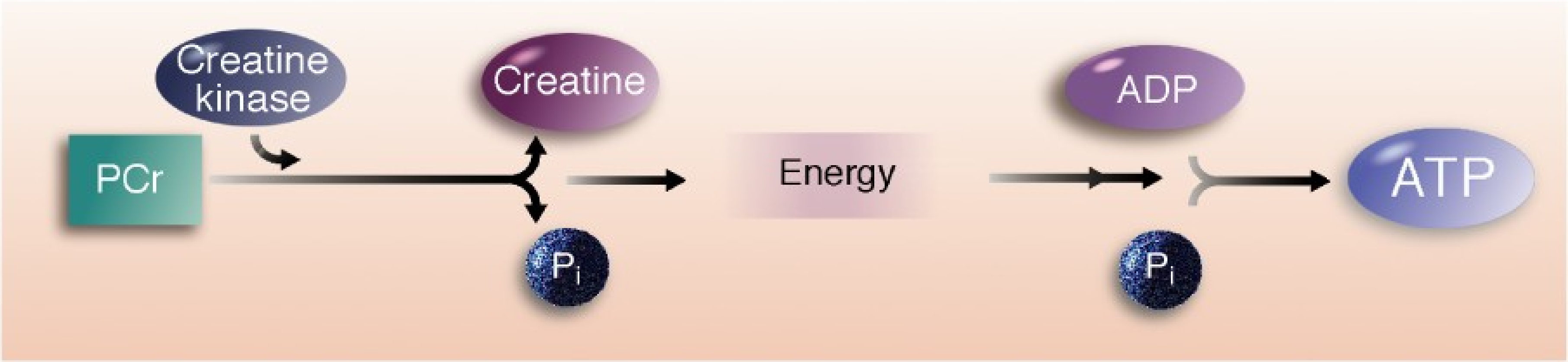
ATP MOLECULE



ATP-PCr System

- This system can prevent energy depletion by quickly reforming ATP from ADP and P_i.
- This process is anaerobic—it occurs without oxygen.
- 1 mole of ATP is produced per 1 mole of phosphocreatine (PCr). The energy from the breakdown of PCr is not used for cellular work but solely for regenerating ATP.

RECREATING ATP WITH PCr



Glycogen Breakdown and Synthesis

Glycolysis—Breakdown of glucose; may be anaerobic or aerobic

Glycogenesis—Process by which glycogen is synthesized from glucose to be stored in the liver

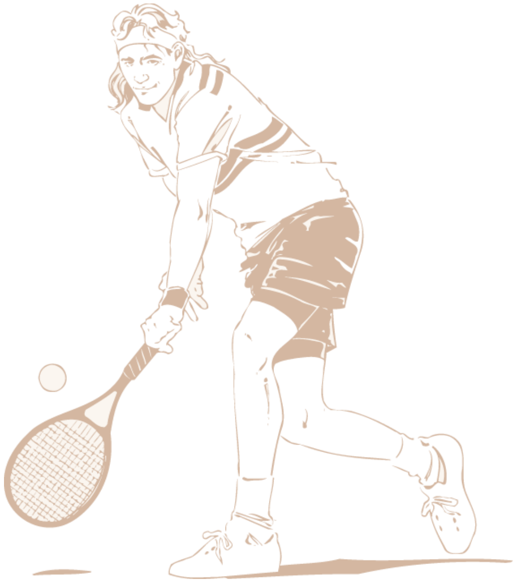
Glycogenolysis—Process by which glycogen is broken into glucose-1-phosphate to be used by muscles

Glycolytic System

- Requires 12 enzymatic reactions to breakdown glucose and glycogen into ATP
- Glycolysis that occurs in glycolytic system is generally anaerobic (without oxygen)
- The pyruvic acid produced by anaerobic glycolysis becomes lactic acid
- 1 mole of glycogen produces 3 mole ATP; 1 mole of glucose produces 2 mole of ATP. The difference is due to the fact that it takes 1 mole of ATP to convert glucose to glucose-6-phosphate, where glycogen is converted to glucose-1-phosphate and then to glucose-6-phosphate without the loss of 1 ATP.

Did You Know…?

The combined actions of the ATP-PCr and glycolytic systems allow muscles to generate force in the absence of oxygen; thus these two energy systems are the major energy contributors during the early minutes of high-intensity exercise.



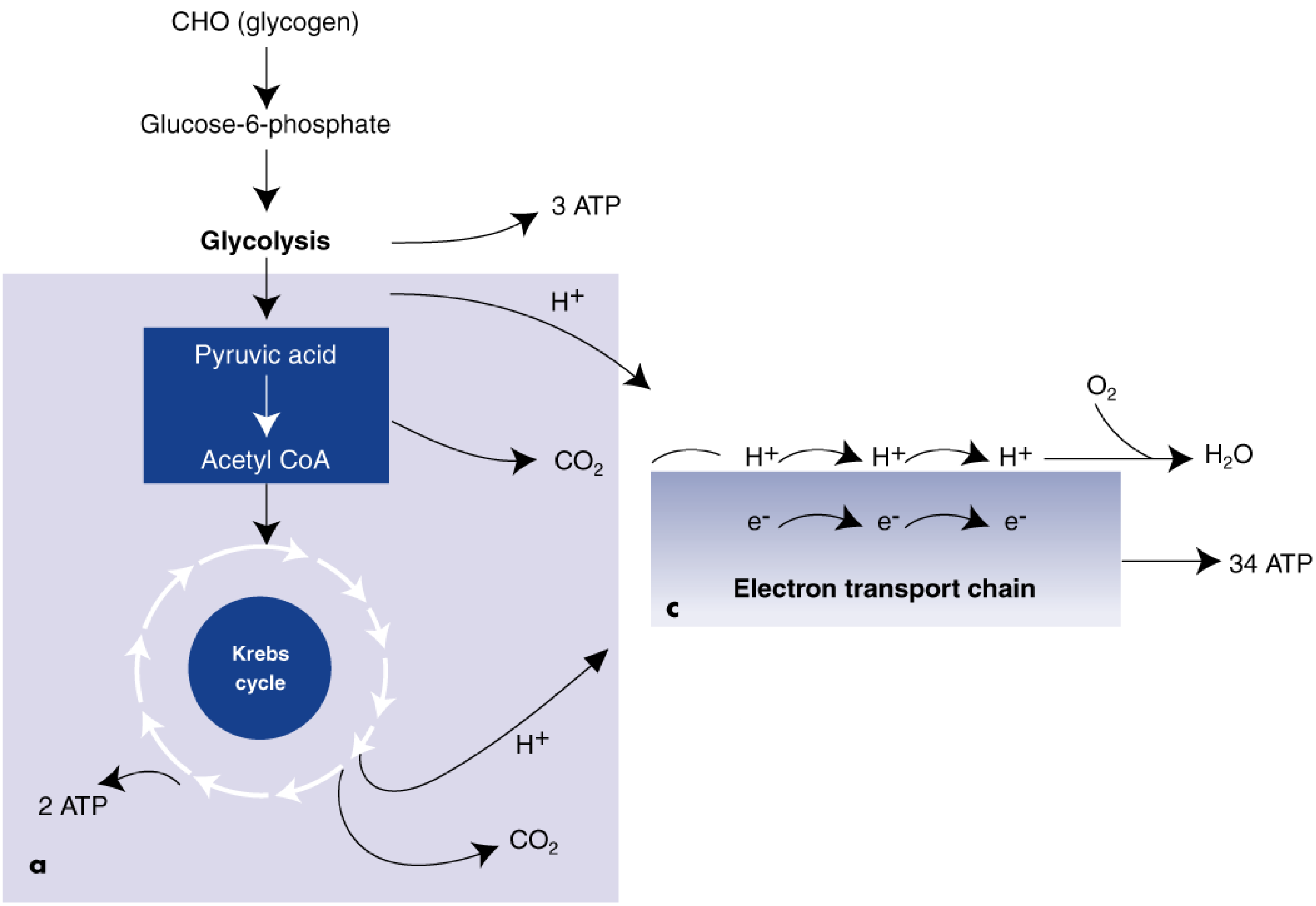
Oxidative System

- Relies on oxygen to breakdown fuels for energy
- Produces ATP in mitochondria of cells
- Can yield much more energy (ATP) than anaerobic systems
- Is the primary method of energy production during endurance events

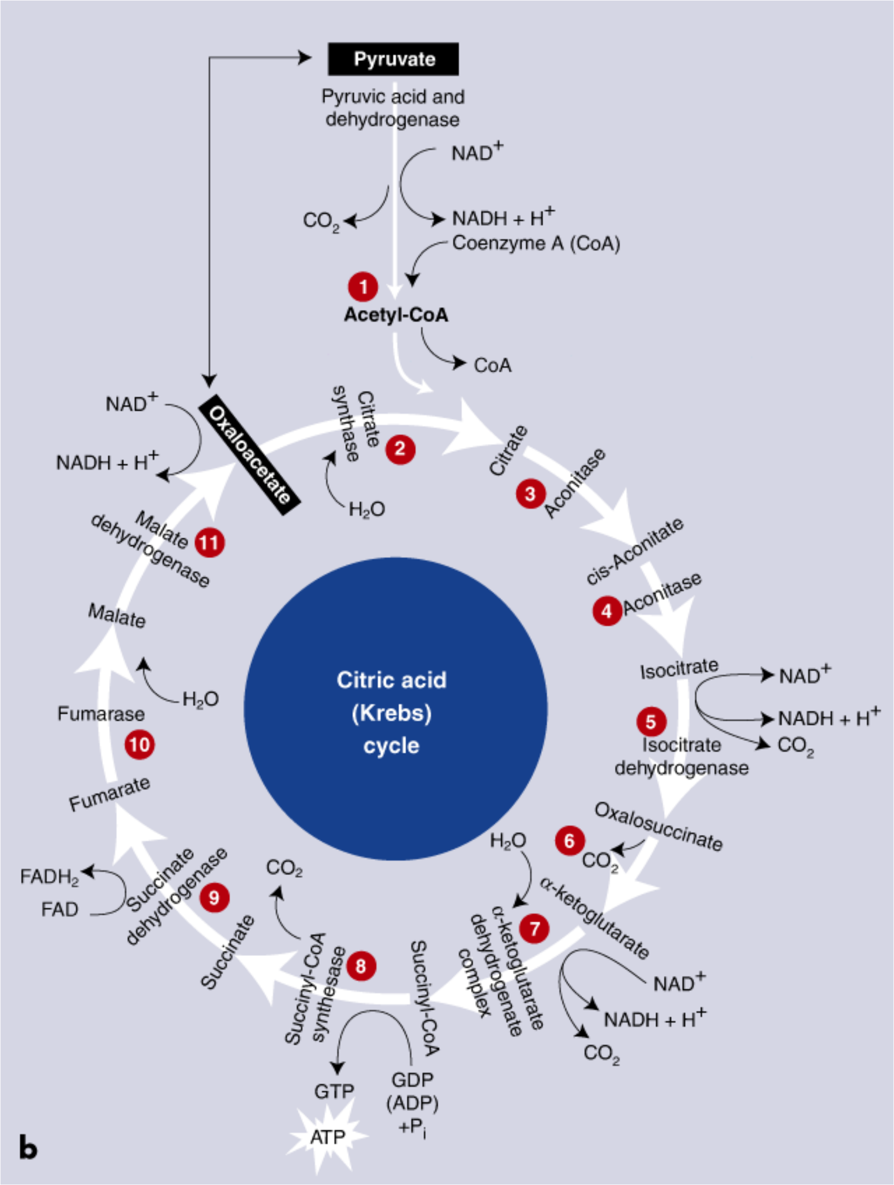
Oxidative Production of ATP

1. Aerobic glycolysis—cytoplasm
2. Krebs cycle—mitochondria
3. Electron transport chain—mitochondria

AEROBIC GLYCOLYSIS AND THE ELECTRON TRANSPORT CHAIN



KREBS CYCLE

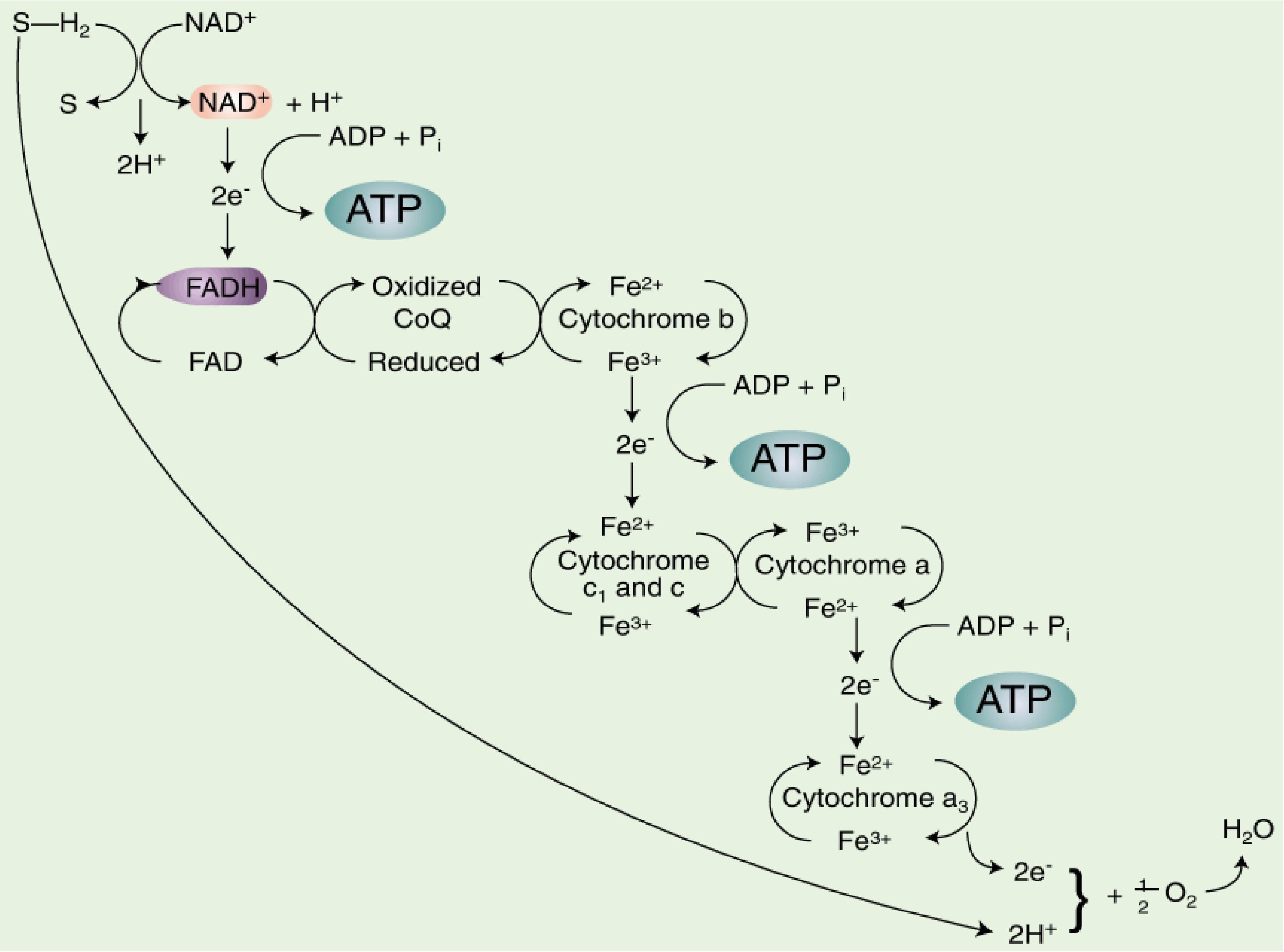


Pyruvate
Pyruvic acid and dehydrogenase
NAD+
CO2
NADH + H+
Coenzyme A (CoA)
1
Acetyl-CoA
CoA
Citrate synthase
2
H2O
Oxaloacetate
NAD+
NADH + H+
Citrate
3
Aconitase
cis-Aconitate
4
Aconitase
Isocitrate
NAD+
NADH + H+
CO2
5
Isocitrate dehydrogenase
Oxalosuccinate
6
CO2
H2O
α-ketoglutarate
7
α-ketoglutarate dehydrogenate complex
NAD+
NADH + H+
CO2
Succinyl-CoA
8
Succinyl-CoA synthesase
GDP (ADP) +Pi
GTP
ATP
CO2
Succinate
9
Succinate dehydrogenase
FADH2
FAD
Fumarate
10
Fumarase
H2O
Malate
11
Malate dehydrogenase
Citric acid (Krebs) cycle
b

Oxidation of Carbohydrate

1. Pyruvic acid from glycolysis is converted to acetyl coenzyme A (acetyl CoA).
2. Acetyl CoA enters the Krebs cycle and forms 2 ATP, carbon dioxide, and hydrogen.
3. Hydrogen in the cell combines with two coenzymes that carry it to the electron transport chain.
4. Electron transport chain recombines hydrogen atoms to produce ATP and water.
5. One molecule of glycogen can generate up to 39 molecules of ATP.

OXIDATIVE PHOSPHORYLATION



Oxidation of Fat

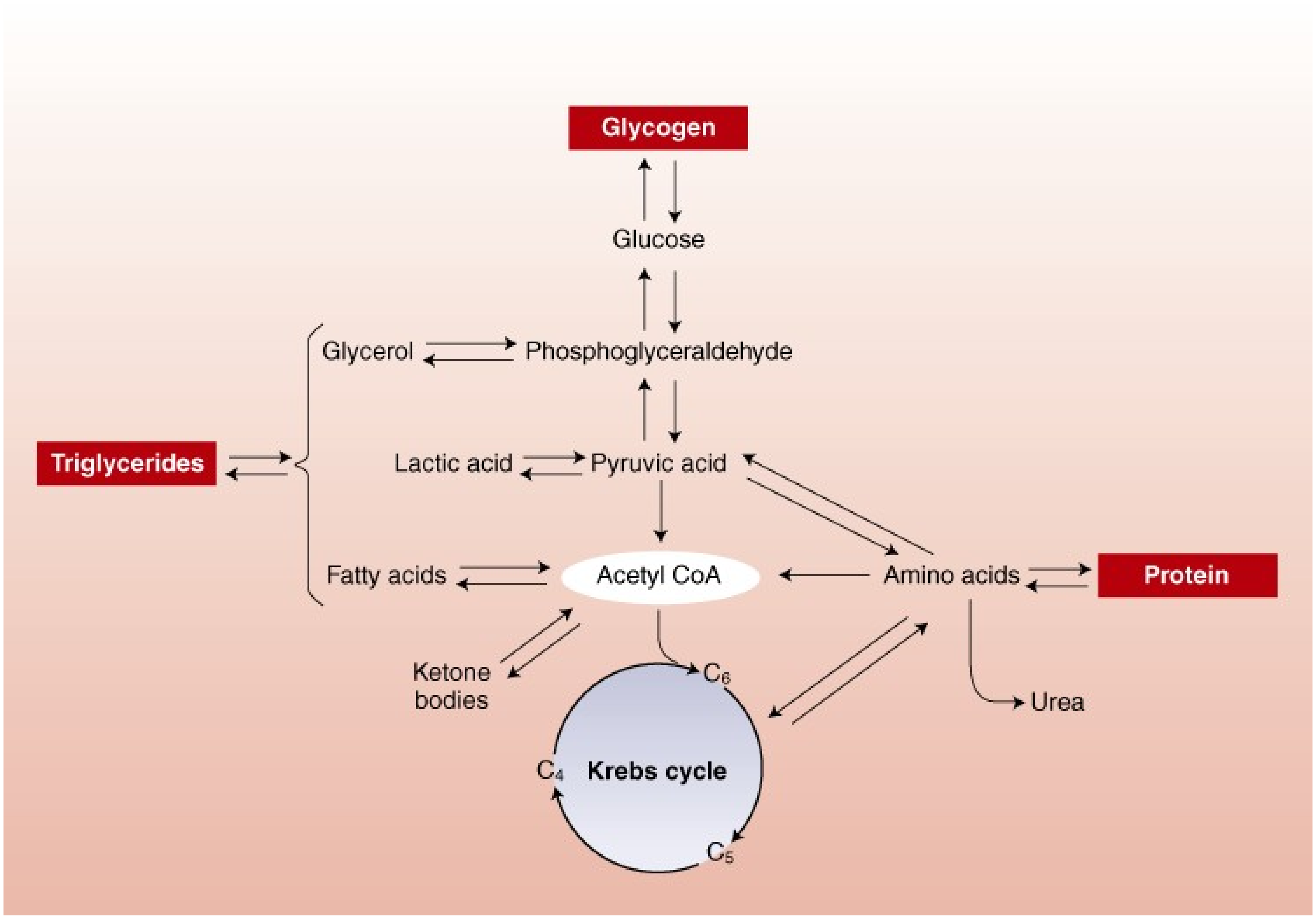
- Lypolysis—breakdown of triglycerides into glycerol and free fatty acids (FFAs).
- FFAs travel via blood to muscle fibers and are broken down by enzymes in the mitochondria into acetic acid which is converted to acetyl CoA.
- Aceytl CoA enters the Krebs cycle and the electron transport chain.
- Fat oxidation requires more oxygen and generates more energy than carbohydrate oxidation.

Energy Production From the Oxidation of Liver Glycogen

Stage of process	Direct	By oxidative phosphorylation[a]
Glycolysis (glucose to pyruvic acid)	3	4-6[b]
Pyruvic acid to acetyl coenzyme A	0	6
Krebs cycle	2	22
Subtotal	5	32-34
Total	37-39	

[a]Refers to adenosine triphosphate (ATP) produced by transferring H^+ and electrons to the electron transport chain. [b]The energy yield differs depending on whether reduced nicotinamide adenine dinucleotide (NADH) or reduced flavin adenine dinucleotide (FADH) is the carrier molecule to transport the electron through the mitochondrial membrane and the electron transport chain, with NADH yielding up to 39 molecules of a ATP and FADH yielding 37 molecules of ATP.

METABOLISM OF FAT



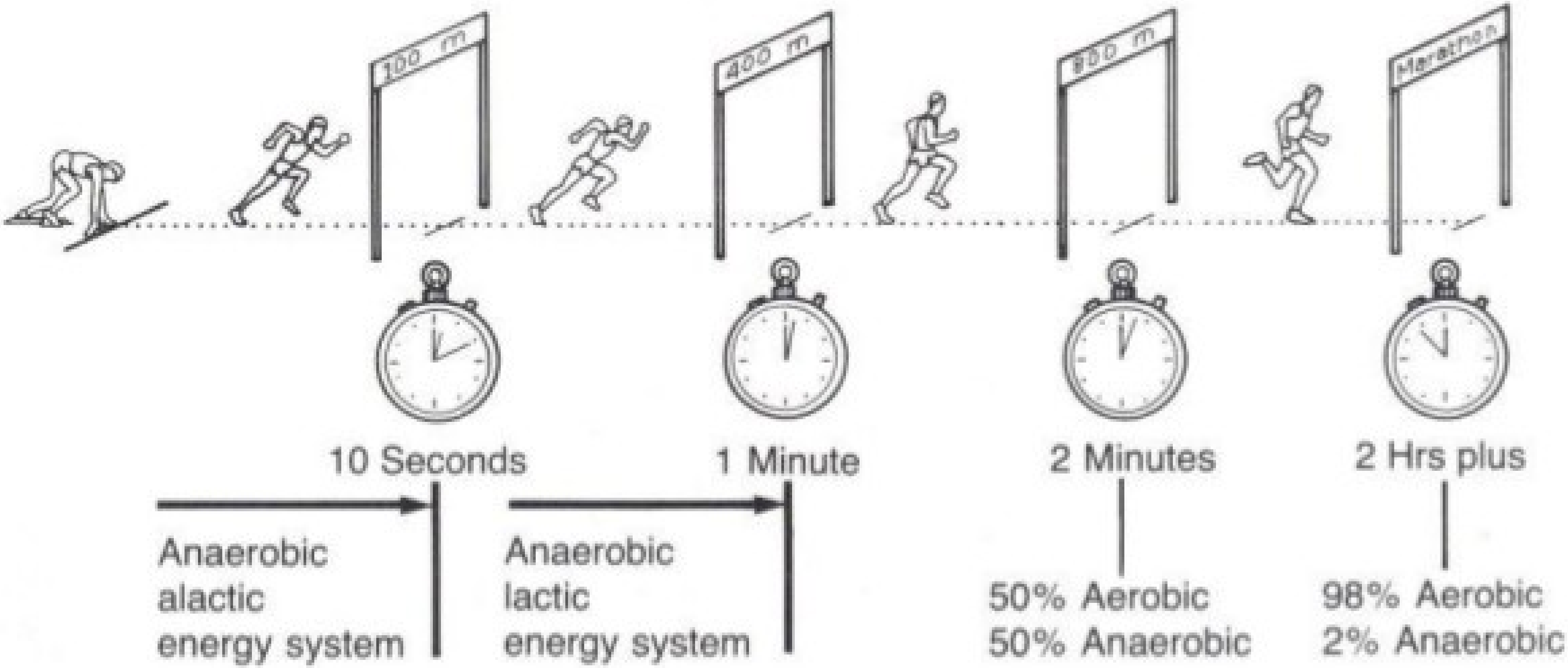
Energy Production From the Oxidation of Palmitic Acid ($C_{16}H_{32}O_2$)

	Adenosine triphosphate produced from 1 molecule of palmitic acid	
Stage of process	**Direct**	**By oxidative phosphorylation**
Fatty acid activation	0	–2
□-oxidation	0	35
Krebs cycle	8	88
Subtotal	8	121
Total	129	

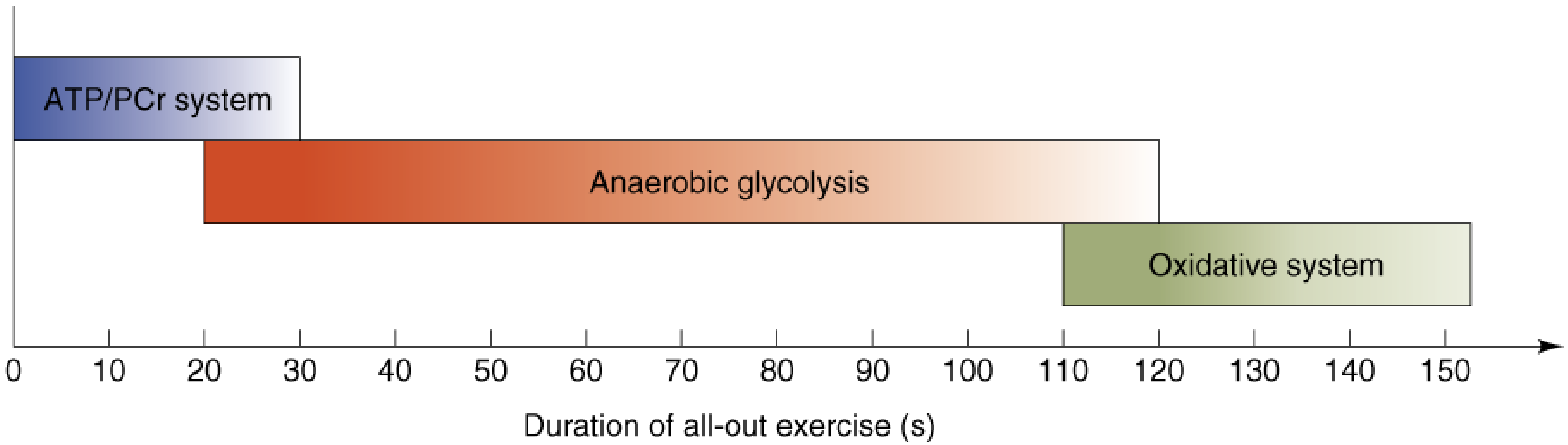
Protein Metabolism

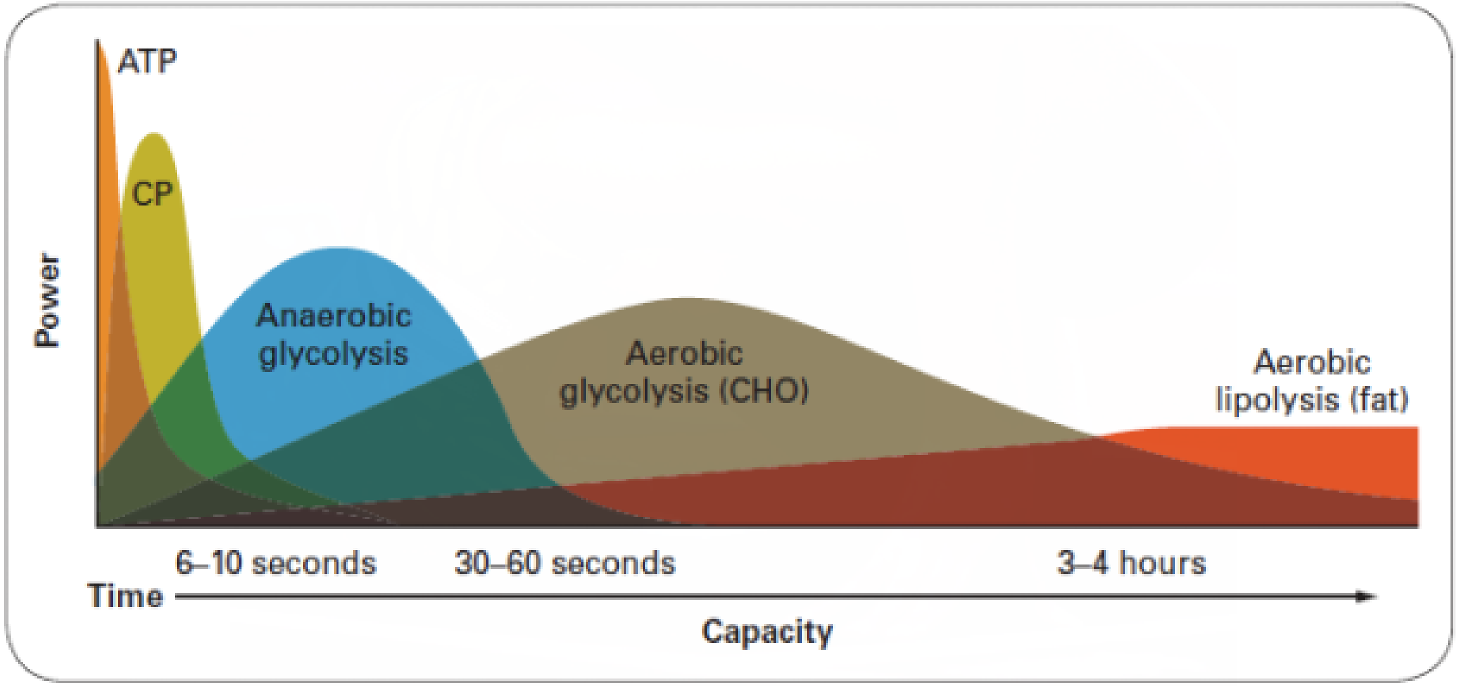
- Body uses little protein during rest and exercise (less than 5% to 10%).
- Some amino acids that form proteins can be converted into glucose.
- The nitrogen in amino acids (which cannot be oxidized) makes the energy yield of protein difficult to determine.

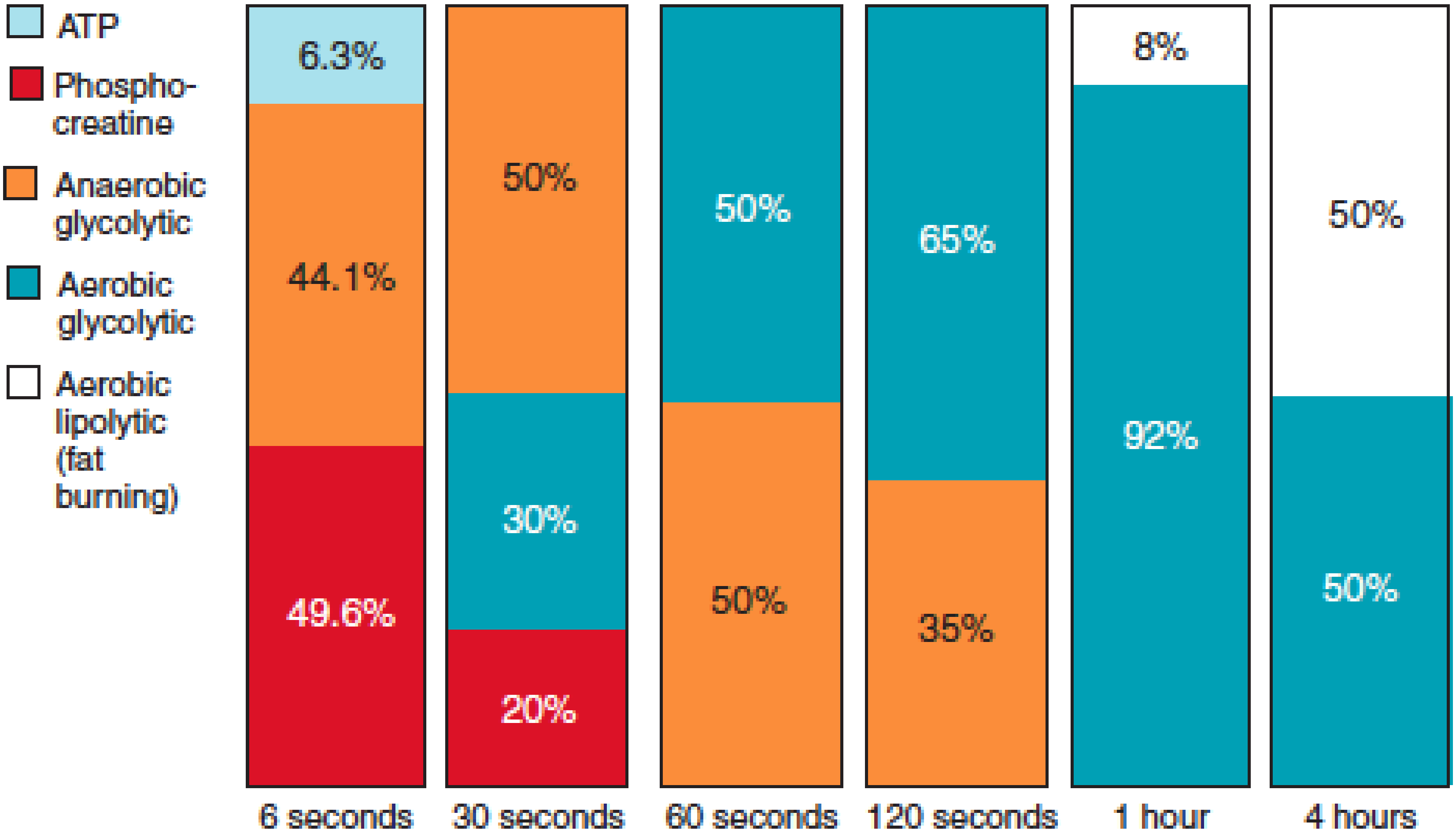
Energy System For Selected Sports



INTERACTION OF ENERGY SYSTEMS ILLUSTRATING THE PREDOMINANT ENERGY SYSTEM







ATP
Phospho-creatine
Anaerobic glycolytic
Aerobic glycolytic
Aerobic lipolytic (fat burning)
6.3%
44.1%
49.6%
50%
30%
20%
50%
50%
65%
35%
8%
92%
50%
50%
6 seconds
30 seconds
60 seconds
120 seconds
1 hour
4 hours

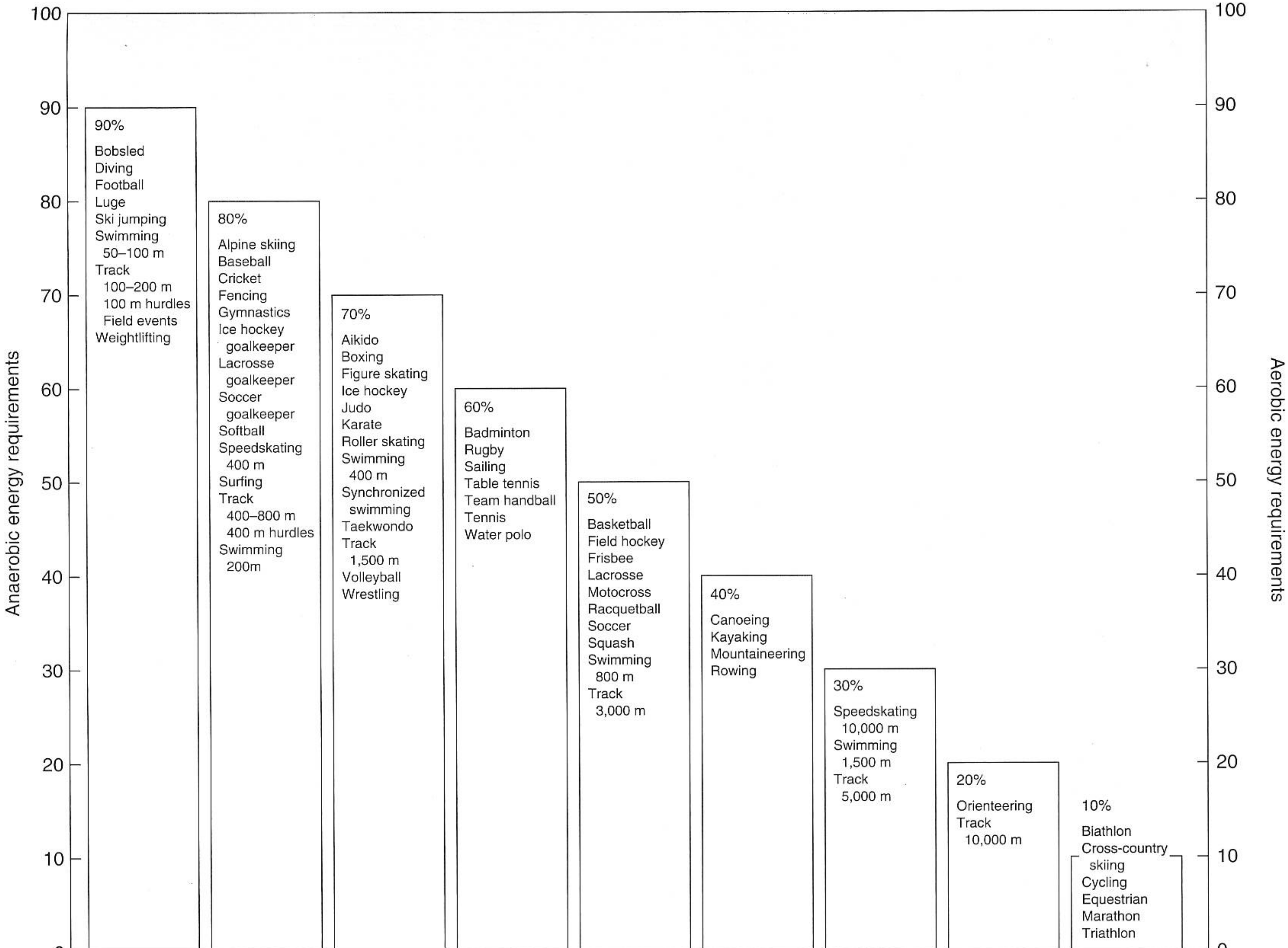


FIGURE 8.1 Anaerobic and aerobic energy requirements for different sports.

Reprinted, by permission, from B.J. Sharkey, 1986, *Coaches guide to sport physiology* (Champaign, IL: Human Kinetics), 100.

What Determines Oxidative Capacity?

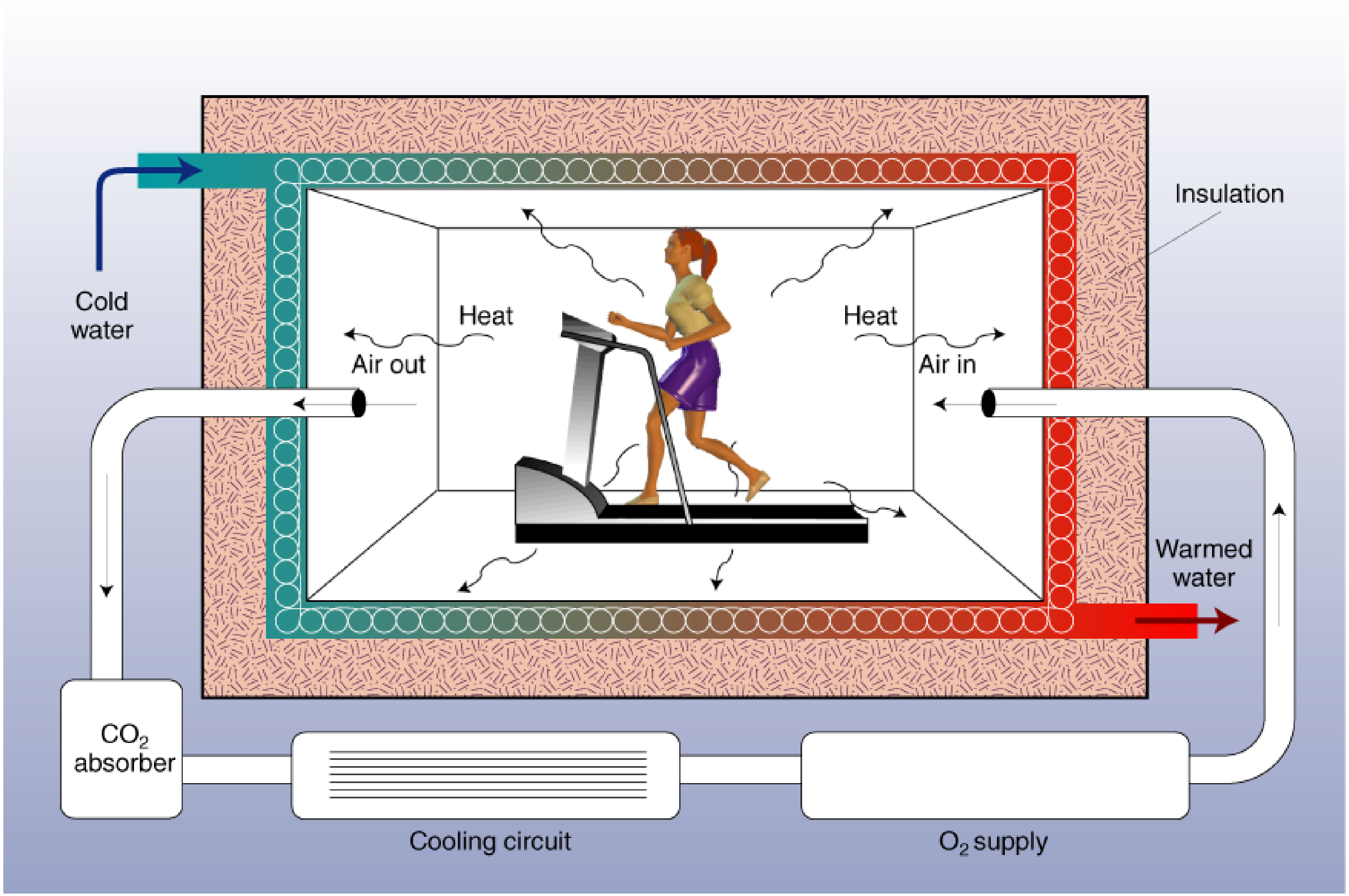
- Oxidative enzyme activity within the muscle
- Fiber-type composition and number of mitochondria
- Endurance training
- Oxygen availability and uptake in the lungs

Measuring Energy Costs of Exercise

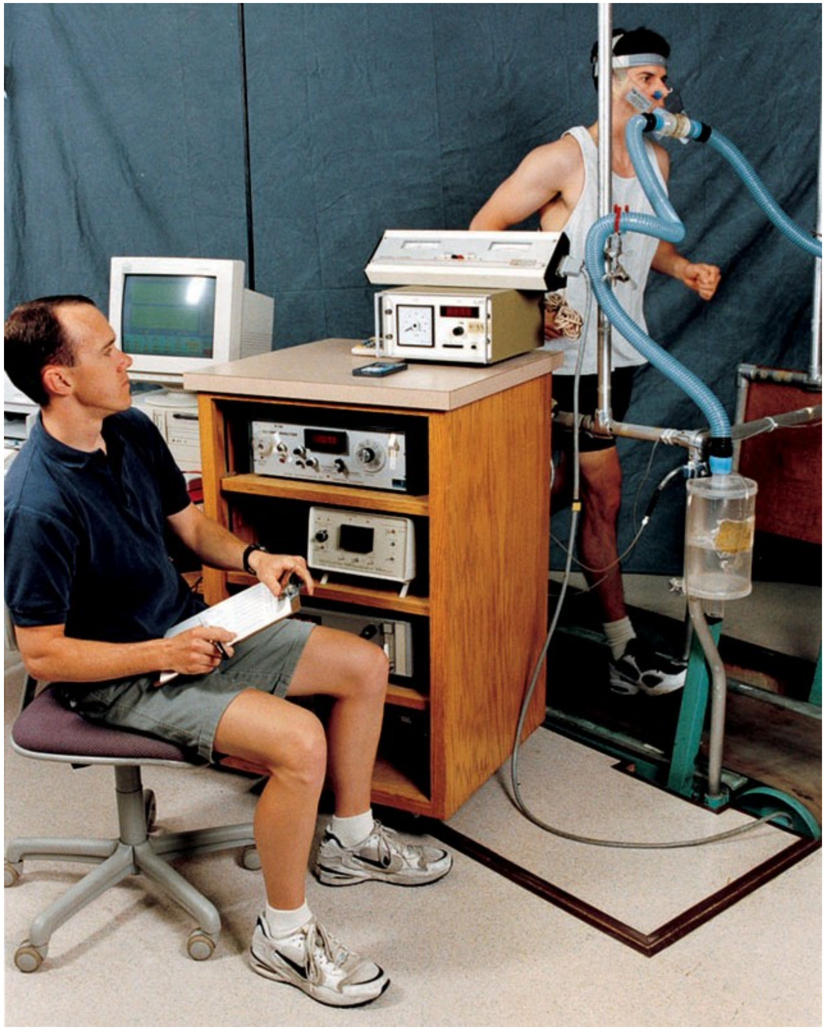
Direct calorimetry—measures the body's heat production to calculate energy expenditure.

Indirect calorimetry—calculates energy expenditure from the respiratory exchange ratio (RER) of $\dot{V}CO_2$ and $\dot{V}O_2$.

CALORIMETRIC CHAMBER

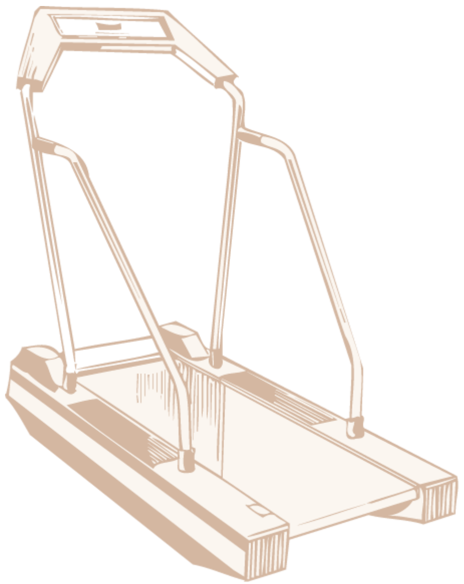


MEASURING RESPIRATORY GAS EXCHANGE



Respiratory Exchange Ratio

- The ratio between CO_2 released ($\dot{V}CO_2$) and oxygen consumed ($\dot{V}O_2$)
- RER = $\dot{V}CO_2/\dot{V}O_2$
- The RER value at rest is usually 0.78 to 0.80
- The RER value can be used to determine energy substrate used at rest and during exercise, with a value of 1.00 indicating CHO and 0.70 indicating fat.



Caloric Equivalence of the Respiratory Exchange Ratio (RER) and % kcal From Carbohydrates and Fats

	Energy	% kcal	
RER	**kcal/L O_2**	**Carbohydrates**	**Fats**
0.71	4.69	0.0	100.0
0.75	4.74	15.6	84.4
0.80	4.80	33.4	66.6
0.85	4.86	50.7	49.3
0.90	4.92	67.5	32.5
0.95	4.99	84.0	16.0
1.00	5.05	100.0	0.0

Metabolic Rate

- Rate at which the body expends energy at rest and during exercise
- Measured as whole-body oxygen consumption and its caloric equivalent
- Basal or resting metabolic rate (BMR) is the minimum energy required for essential physiological function (varies between 1,200 and 2,400 kcal/24 hr)
- The minimum energy required for normal daily activity is about 1,800 to 3,000 kcal/24 hr

Factors Affecting BMR/RMR

- The more **fat-free mass**, the higher the BMR
- The more **body surface area**, the higher the BMR
- BMR gradually decreases with increasing **age**
- BMR increases with increasing **body temperature**
- The more **stress**, the higher the BMR
- The higher the levels of **thyroxine** and **epinephrine**, the higher the BMR

Caloric Equivalents

- Food energy equivalents

CHO:	4.1 kcal/g
Fat:	9.4 kcal/g
Protein:	4.1 kcal/g

- Energy per liter of oxygen consumed

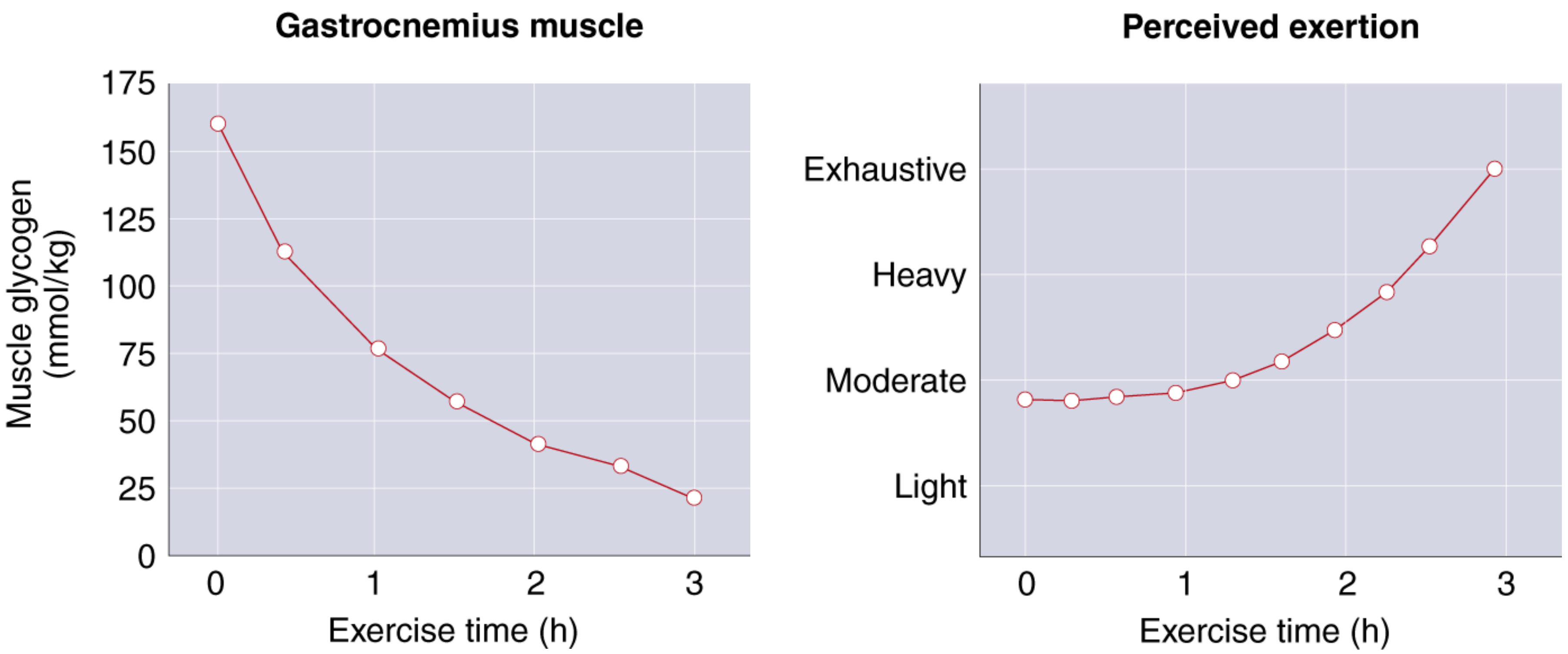
CHO:	5.0 kcal/L
Fat:	4.7 kcal/L
Protein:	4.5 kcal/L

Example: $\dot{V}O_2$ rest = 0.300 L/min ´ 60 min/hr ´ 24 hr/day = 432 L/day ´ 4.8 kcal/L = 2,074 kcal/day

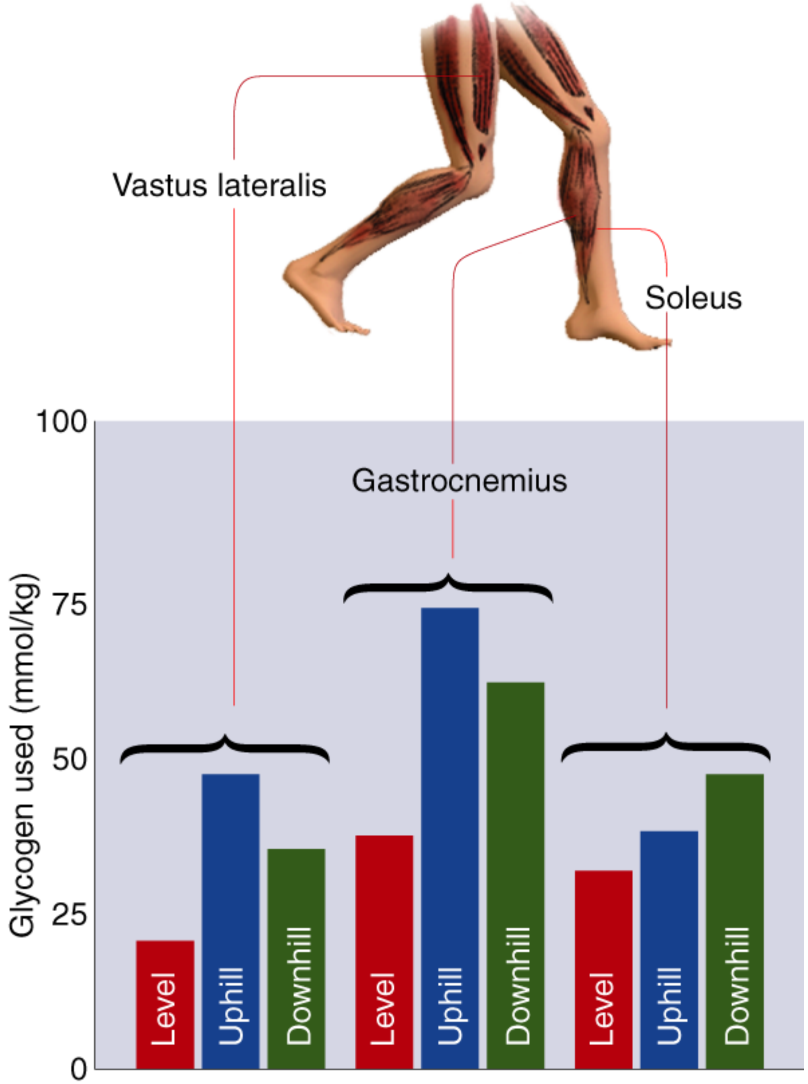
Factors Influencing Energy Costs

- Type of activity
- Activity level
- Age
- Sex
- Size, weight, and body composition
- Intensity of the activity
- Duration of the activity
- Efficiency of movement

USE OF MUSCLE GLYCOGEN DURING EXERCISE



GLYCOGEN USE DURING RUNNING



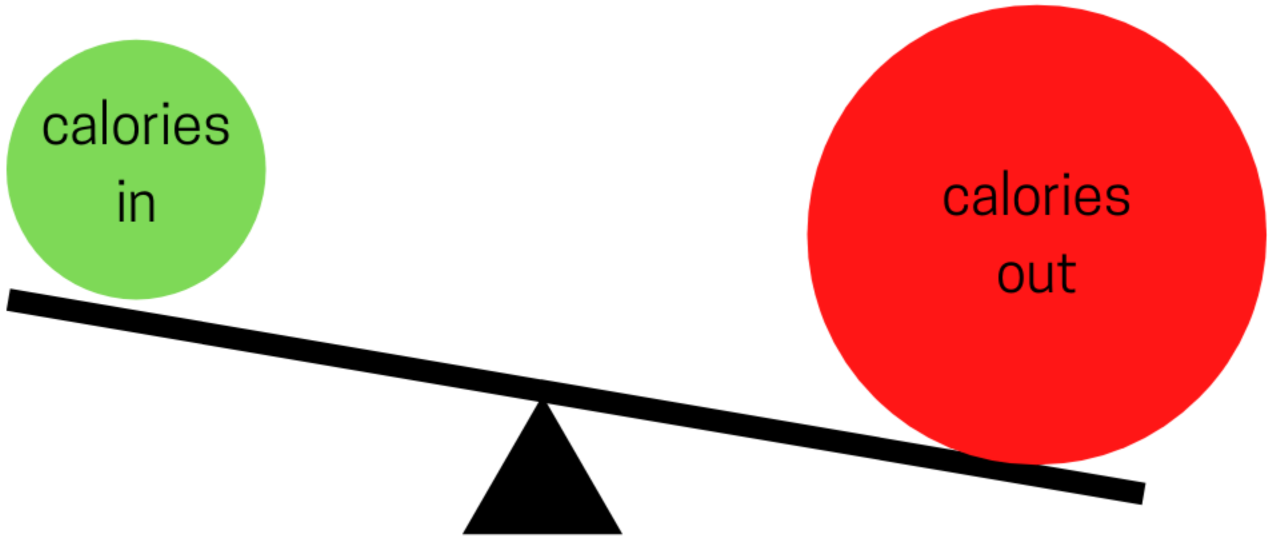
Mean Energy expenditure (EE) per day in kJ.

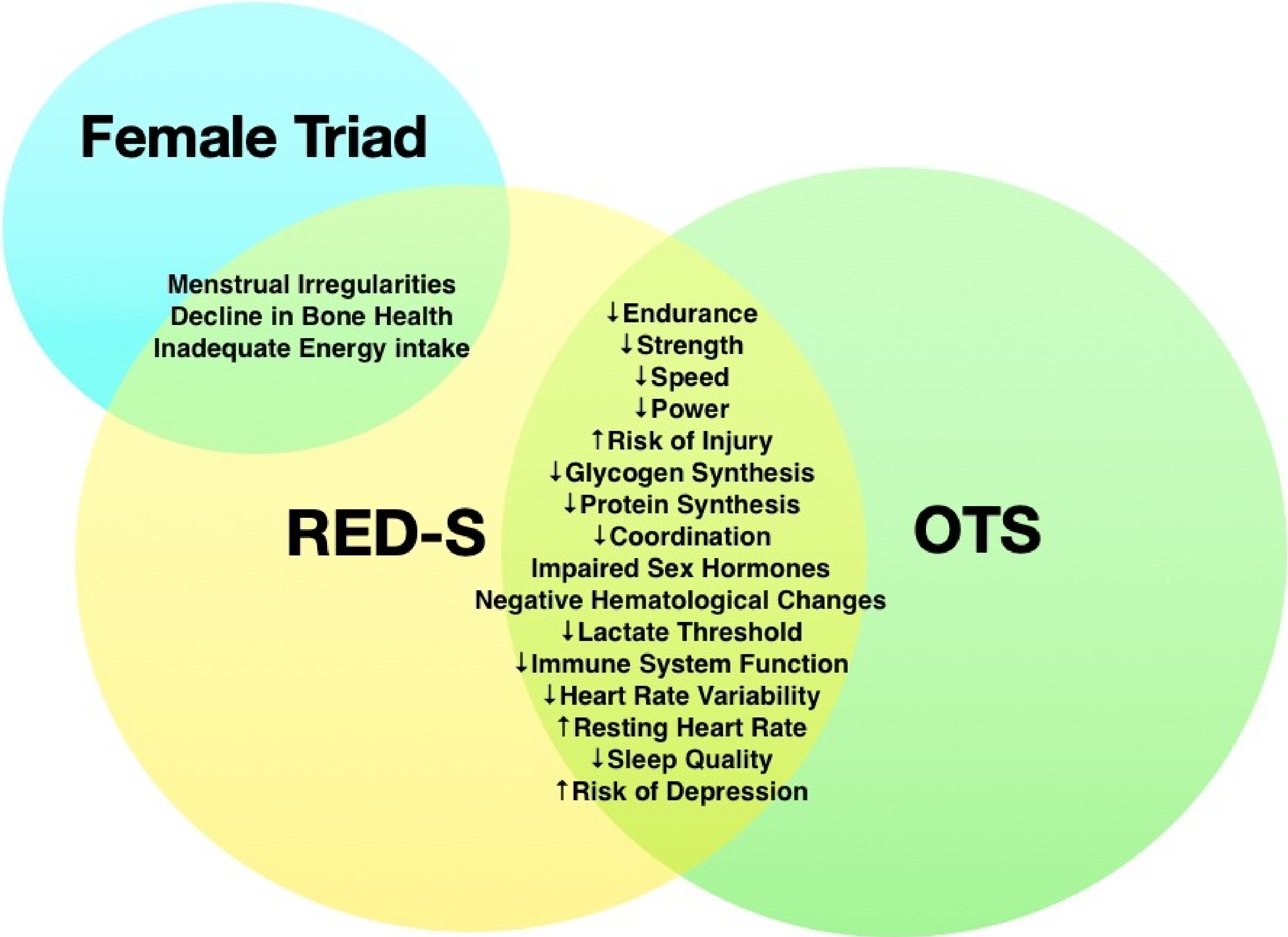
Female (20 – 30 years old)				
Height	Weight	No activity	Medium activity	High activity
160 cm	50 kg	7500	8600	9100
	60 kg	8200	9200	10100
170 cm	60 kg	8200	9200	10100
	70 kg	8900	10000	11100
180 cm	70 kg	8900	10000	11000
	80 kg	9600	10800	12100

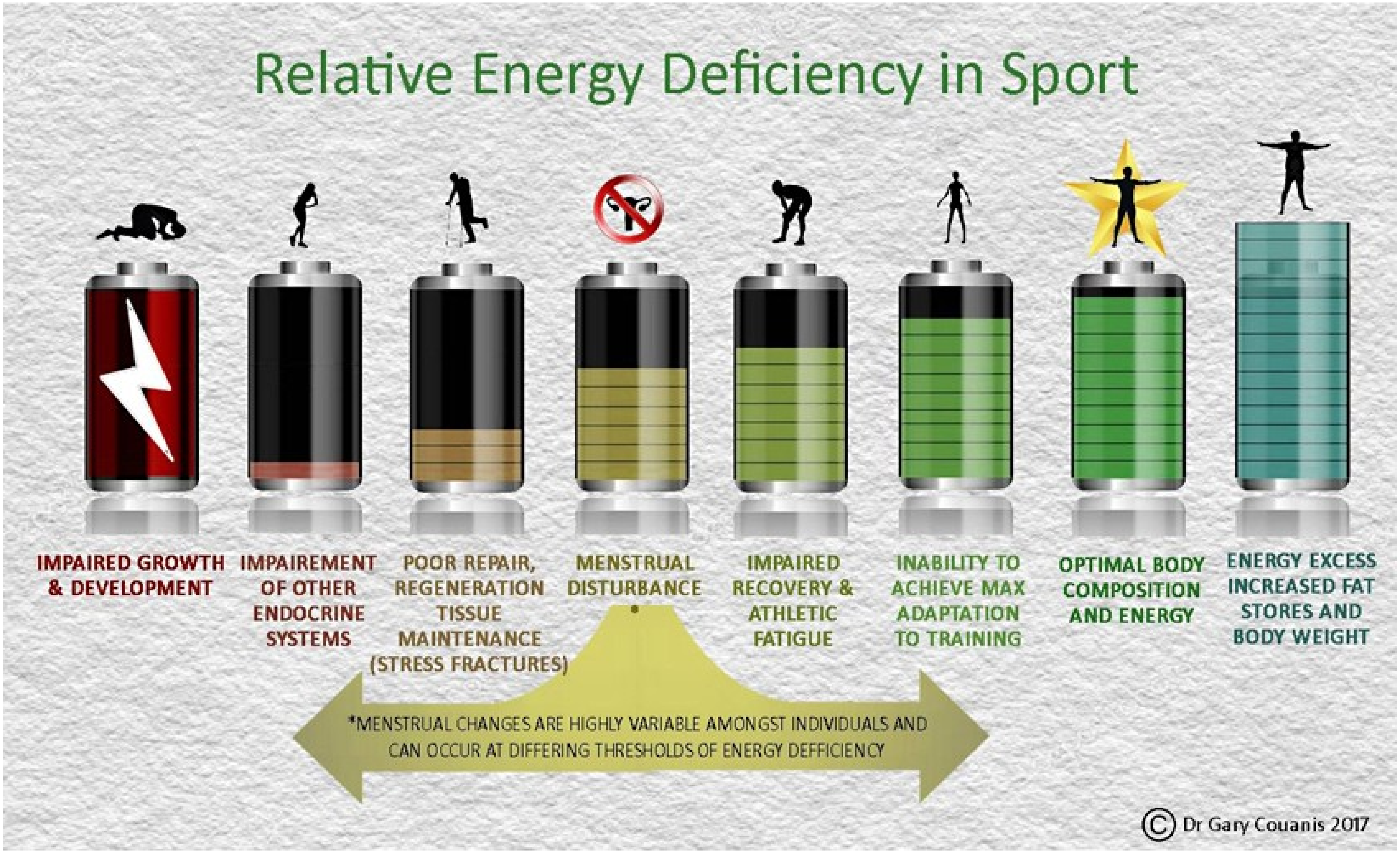
Mean Energy expenditure (EE) per day in kJ.

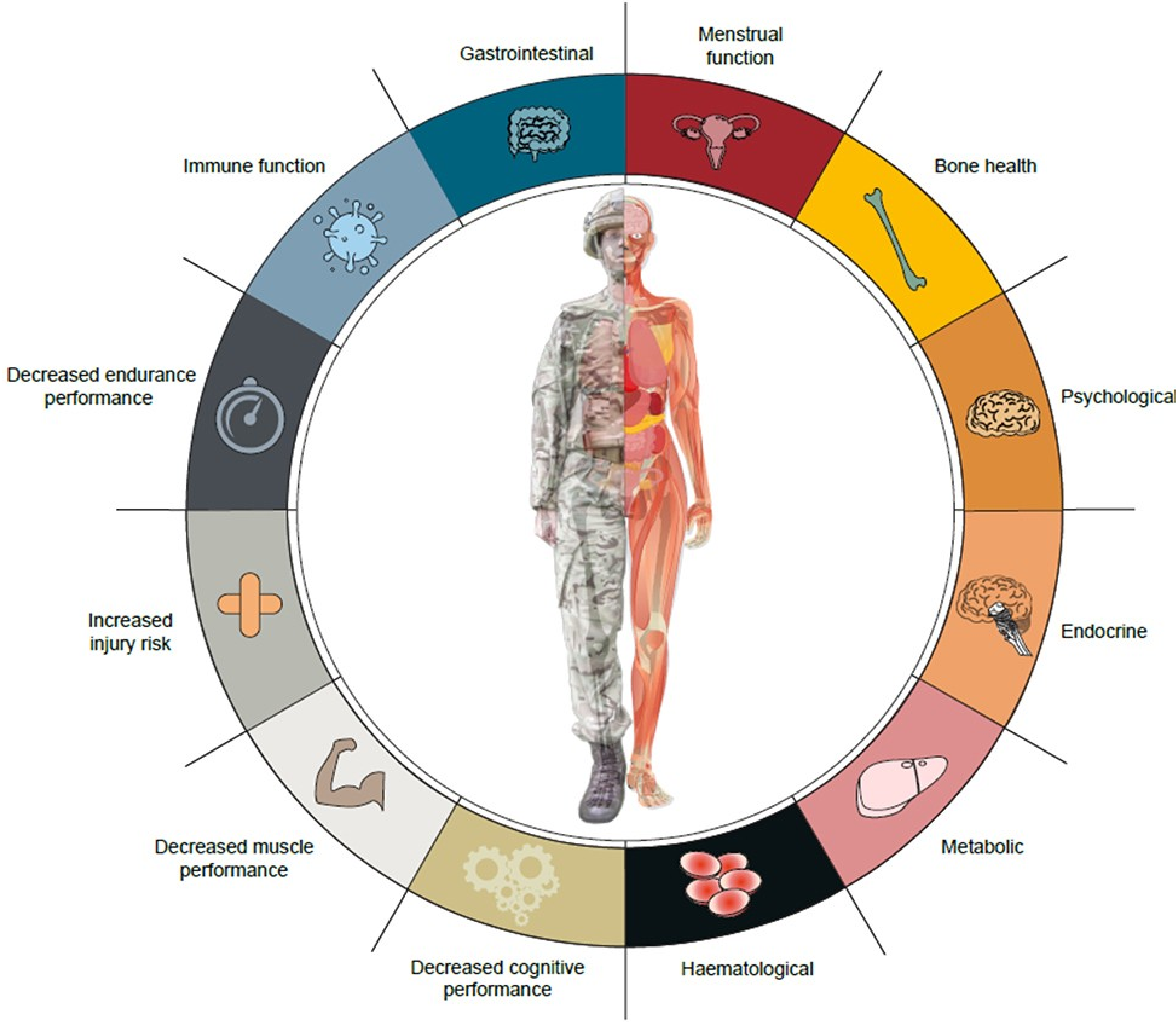
Male (20-30 years old)				
Height	Weight	No activity	Medium activity	High activity
170 cm	60 kg	9800	10800	11800
	70 kg	10500	11500	12500
180 cm	70 kg	10500	11500	12500
	80 kg	11300	12400	13500
190 cm	80 kg	11300	12400	13500
	90 kg	12200	13000	14100

ENERGY DEFICIENCY




Female Triad
Menstrual Irregularities
Decline in Bone Health
Inadequate Energy intake
RED-S
OTS
↓Endurance
↓Strength
↓Speed
↓Power
↑Risk of Injury
↓Glycogen Synthesis
↓Protein Synthesis
↓Coordination
Impaired Sex Hormones
Negative Hematological Changes
↓Lactate Threshold
↓Immune System Function
↓Heart Rate Variability
↑Resting Heart Rate
↓Sleep Quality
↑Risk of Depression


Relative Energy Deficiency in Sport
IMPAIRED GROWTH & DEVELOPMENT
IMPAIREMENT OF OTHER ENDOCRINE SYSTEMS
POOR REPAIR, REGENERATION TISSUE MAINTENANCE (STRESS FRACTURES)
MENSTRUAL DISTURBANCE *
IMPAIRED RECOVERY & ATHLETIC FATIGUE
INABILITY TO ACHIEVE MAX ADAPTATION TO TRAINING
OPTIMAL BODY COMPOSITION AND ENERGY
ENERGY EXCESS INCREASED FAT STORES AND BODY WEIGHT
*MENSTRUAL CHANGES ARE HIGHLY VARIABLE AMONGST INDIVIDUALS AND CAN OCCUR AT DIFFERING THRESHOLDS OF ENERGY DEFFICIENCY
© Dr Gary Couanis 2017



Gastrointestinal
Menstrual function
Immune function
Bone health
Decreased endurance performance
Psychological
Increased injury risk
Endocrine
Decreased muscle performance
Metabolic
Decreased cognitive performance
Haematological

RED-S

Relative Energy Deficiency in Sport

What is it?

A condition of energy deficiency causing adverse effects on all bodily systems. It affects both **male** and **female** athletes and dancers who do not fuel adequately, either intentionally or unintentionally

Why does it matter?

1. Impaired growth and development
2. Impact on health and wellbeing
3. Adverse effect on performance

Suboptimal performance as a result of RED-S
(Keay, Br J Sports Med 2017)

Recognition & next steps

1. Look out for

- Perfectionist tendencies
- Disordered/restricted eating
- Frequent injuries/niggles
- Illness
- Menstrual dysfunction
- Loss of sex drive

2. Talk to someone

Are you...

- Overtraining?
- Fuelling adequately?
- Taking regular rest days?

3. Seek medical help

- GP needs to rule out other conditions
- GP can refer on to specialist services such as

4. Read more at...

Scan me

\#TRAIN BRAVE

Scan me

Be aware that...

20%

Prevalence of disordered eating is 20% higher amongst athletes compared to non athletes

(Joy et al, Br J Sports Med 2016)

For female athletes

- Regular menstrual cycle is a barometer of hormone health
- Not starting periods by age 16 or not having periods for >6 months requires medical investigation
- Oral contraceptive pill (OCP) can **mask** problems without providing bone protection or addressing underlying cause
- Using OCP for contraception needs to be an informed decision by the athlete

(Gordon et al, J Clin Endocrinol Metab 2017)

Guidelines for conditions of resting measurements
The Academy of Nutrition and Dietetics (AND) :

In preparation, a subject should be fasting for 7 hrs or greater, and mindful to avoid stimulants and stressors, such as caffeine, nicotine, and hard physical activities such as purposeful exercises.

For 30 minutes before conducting the measurement, a subject should be laying supine without physical movements, no reading nor listening to music. The ambiance should reduce stimulation by maintaining constant quiet, low lighting, and steady temperature. These conditions continue during the measurement stage.

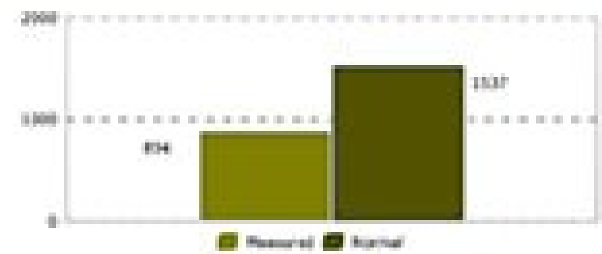
Indirect calorimetry is considered the gold-standard method to measure RMR.

https://cortex-medical.com/EN/MetaSoft-Studio-en.htm

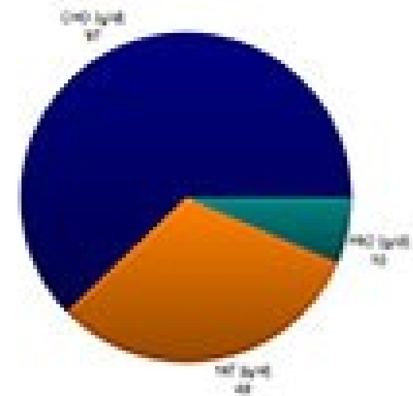
Device	MetaLyzer 3B-R3	Ambient Conditions	
		Temperature	21.9°C
		Pressure	1015mBar

Results

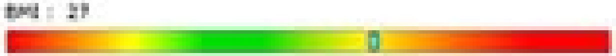
RMR	**894 kcal/d**
Normal	1537 kcal/d
RMR/Weight	12.4 kcal/d/kg
RMR/BSA	503 kcal/d/m2
Deviation Normal	-42 %



Variable	Unit	Value
V'O2	L/min	0.13
V'CO2	L/min	0.11
RQ		0.83
RMR/kg	kcal/d/kg	12.4
RMR/BSA	kcal/d/m2	503
CHO	g/d	97
FAT	g/d	49
PRO	g/d	10
EECHO	kcal/h	17
EEFAT	kcal/h	19
EEPRO	kcal/h	2

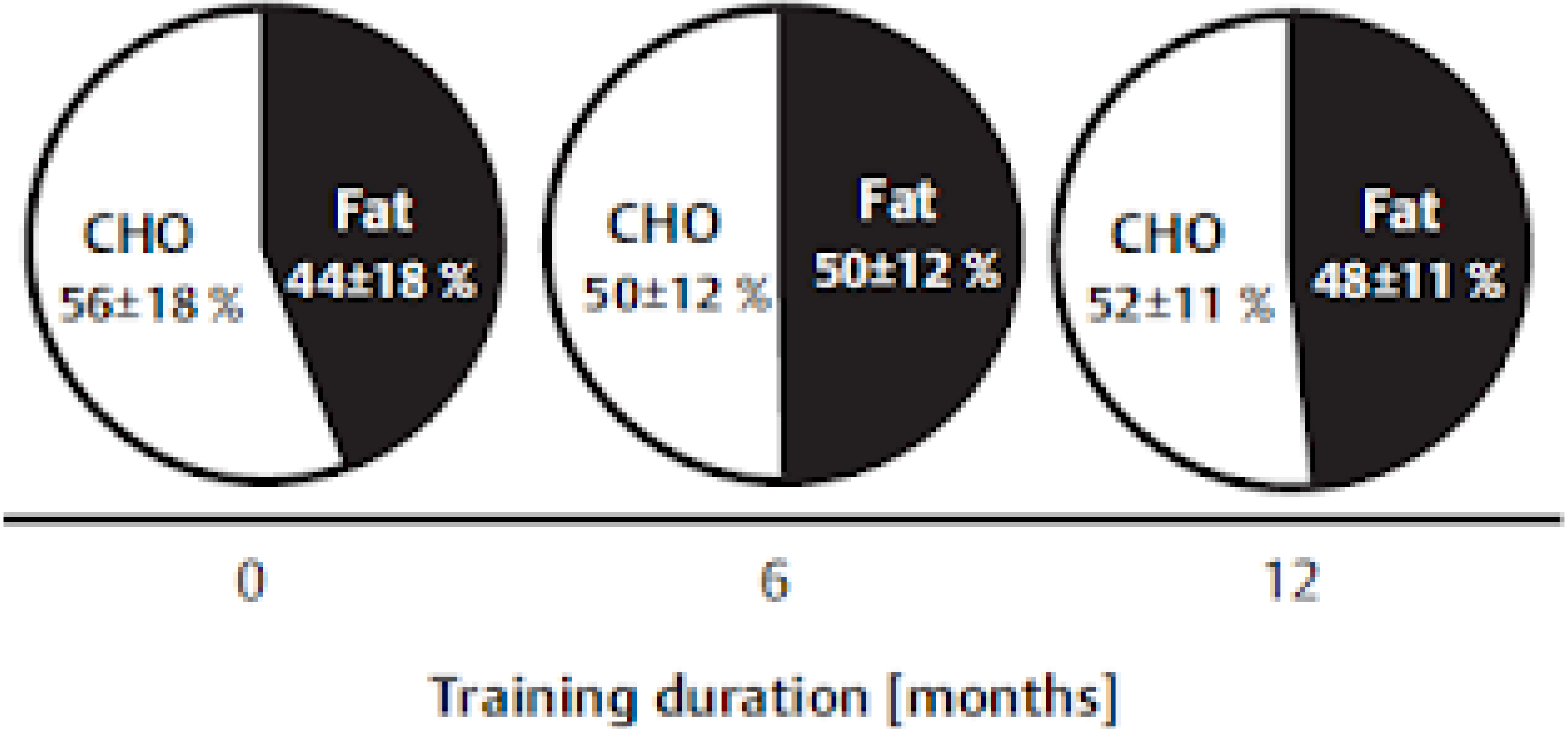


BMI : 27

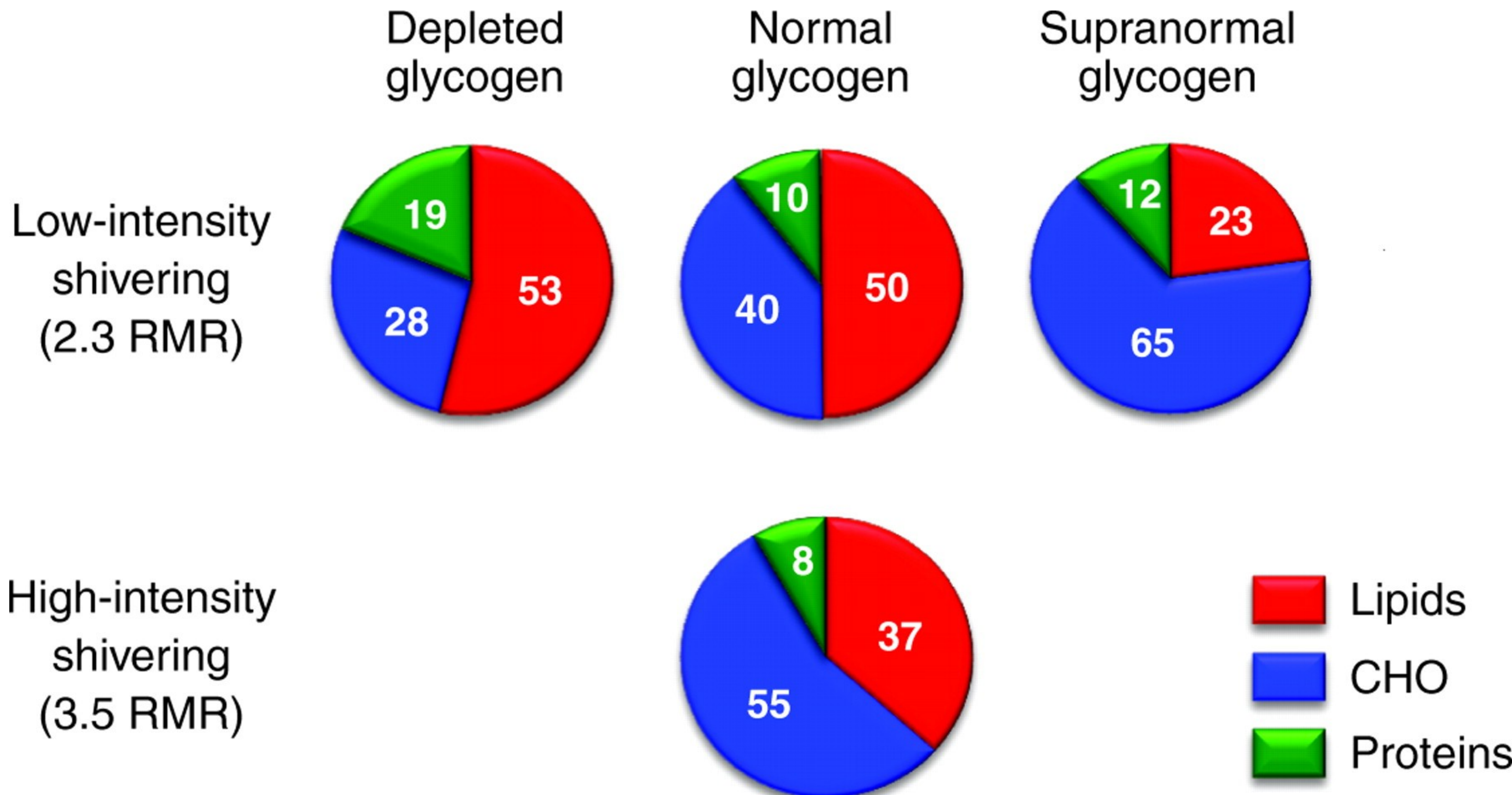


Data Conditioning and Steady State

Applied data conditioning	Moving data points average, 3
Steady state interval	0:31:55, 0:00:00 after test start
Deviation of V'O2 [%]	157.9
Deviation of V'CO2 [%]	155.5
Deviation of RQ [%]	10.3



CHO
56±18 %
Fat
44±18 %
CHO
50±12 %
Fat
50±12 %
CHO
52±11 %
Fat
48±11 %
0
6
12
Training duration [months]



Depleted glycogen
Normal glycogen
Supranormal glycogen
Low-intensity shivering (2.3 RMR)
19
53
28
10
50
40
12
23
65
High-intensity shivering (3.5 RMR)
8
37
55
Lipids
CHO
Proteins