# Energetic metabolism

# Physiology of Exercise

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# Energetic metabolism

= summary of all chemical (and physical) processes included in:

1. **Production of energy from internal and external sources**
2. **Synthesis** and **degradation** of structural and functional tissue components
3. Excretion of **waste products** and **toxins** from body

**Metabolic speed:** amount of energy released per unit of time

**Calorie** (cal) = amount of thermal energy, necessary for warming up 1g of water for 1°C, from 15°C to 16°C



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**SACCHARIDES**

**LIPIDS**

**PROTEINS**

**ENERGY INPUT = ENERGY CONSUMPTION**

| | |
|---|---|
| MECHANIC WORK | Muscle contraction<br>Movement of cells (flagella), organelles |
| SYNTHESIS | Energetic stores production<br>Tissue growth<br>Essential molecules production |
| MEMBRANE TRANSPORT | Minerals<br>Organic substances<br>AA |
| PRODUCTION AND TRANSMISSION OF SIGNALS | Electrical<br>Chemical<br>Mechanical |
| HEAT PRODUCTION | Body temperature control<br>Ineffective chemical reactions |
| DETOXICATION DEGRADATION | Urine production<br>Conjugation<br>Oxidation<br>Reduction |

I. thermodynamic law: At steady state, input of energy equals to its expenditure

Input ⟷ stores

Expenditure of energy = external work + energy stores + heat

Intermediate stages: various chemical, mechanical and thermal reactions

# Energy intake (input)

Saccharides, lipids, proteins

Burning releases: 4.1kcal/g, 9.3kcal/g, 5.3kcal/g (4.1 in body)  1kcal=4184J

Conversion of proteins and saccharides to lipids – effective storage of the energy

Conversion of proteins to saccharides – need of „fast“ energy

BUT: there is no significant conversion of lipids to saccharides

# Energy output

1. **At rest:** basal metabolism; 8 000 kJ / day; 200-250 ml $O_2$/min; directly depends on body mass and surface; decreases with age; increases with ambient temperature; decreases by 10-15% during sleep; genetically determined **75%BM**
2. **After meal:** slight increase in energetic output – specific dynamic effect – e.g. for glycogen formation **7%BM**
3. **In sitting position:** spontaneous physical activity **18%BM**
4. **Facultative thermogenesis:** non-shivering

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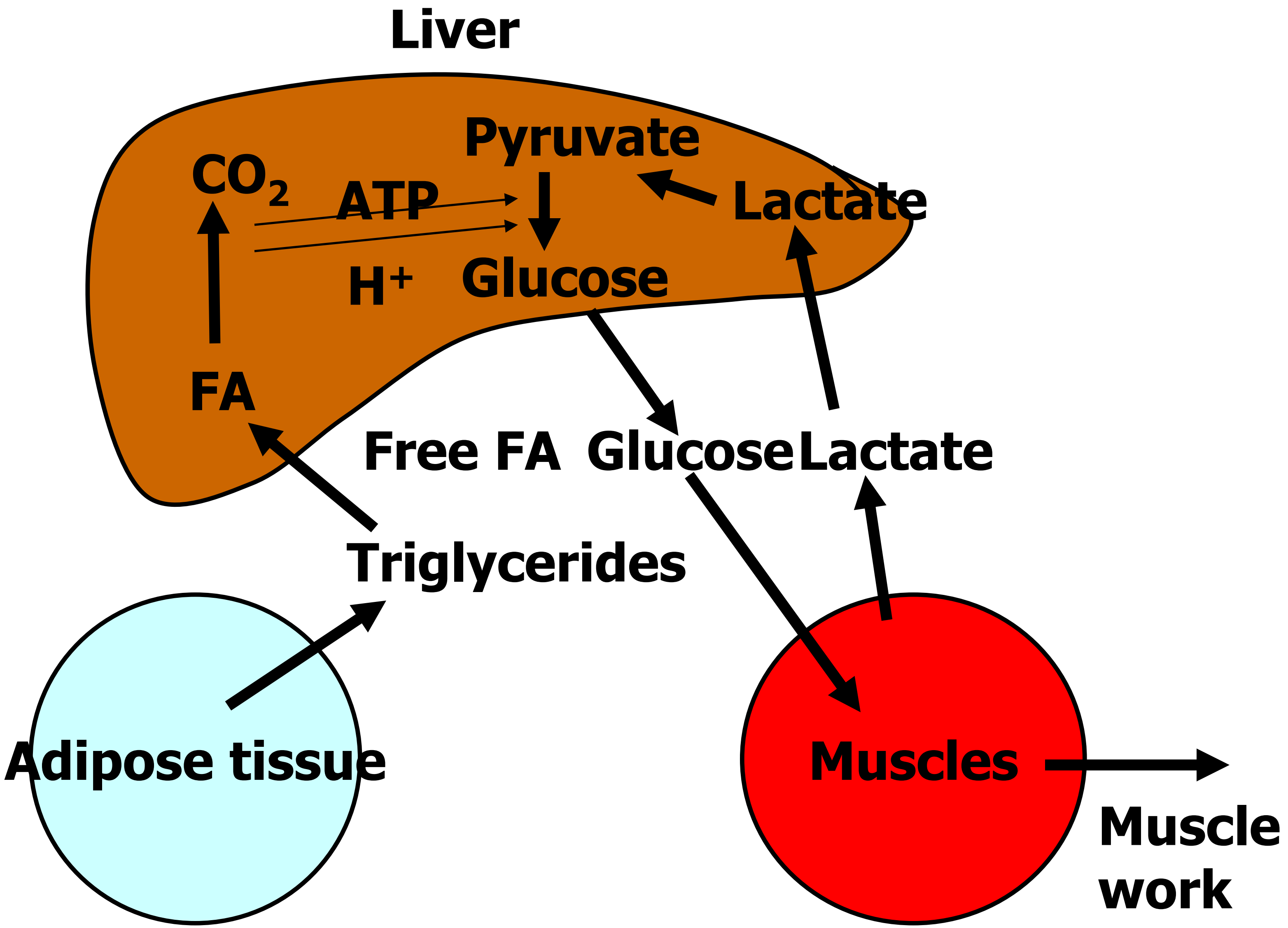
5. **During exercise:** energetically most demanding; individual; changes according to season

# Transport of energy among organs



- Energy **stores**: ATP, creatinphosphate, GTP, CTP (cytosin), UTP (uridin), ITP (inosin)
- Macroergic bond – 12kcal/mol
- Efficiency is not 100% - 18kcal of substrate needed for 1 bond in ATP
- Daily: 63 kg of ATP (128mol)
- Glycolysis: only short-lasting source of energy (2 pyruvates – only approx. 8% of glucose energy);

supply of glucose is limited, lactate

# RESPIRATORY QUOTIENT

**RQ** = $V_{CO2} : V_{O2}$

(per unit of time, at steady state)

Saccharides: RQ = 1
Lipids: RQ = 0.7
Proteins: RQ = 0.8

**R** – ratio of respiratory exchange (no steady state!)



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# Storage and transport of energy

- Both input and output of energy are irregular – necessity of storage
- **75%** of stores: triglycerides (9kcal/g) in adipose tissue (10-30% of body mass), lasts up to 2 months ; source – dietary FA and esterification with a-glycerolphosphate or synthesis from acetylCoA (from glycolysis) – saccharides are converted to more effective store of energy = lipids
- **25%** of stores: proteins (4kcal/g); conversion to saccharides (gluconeogenesis during stress); adverse effects on organism
- Less than **1%** of stores: saccharides (4kcal/g) as glycogen; important for CNS!!! and short-term enormous exercise; ¼ of glycogen stores in liver (75-100g), rest in muscles (300-400g); liver glycogen – glycogenolysis – release of glucose; muscle glycogen – used only in muscles (no glukoso-6-phosphatase)
- Gluconeogenesis: from pyruvate, lactate and glycerol and AA (except of leucin);NO from acetyl-CoA
- Storage and transport of energy requires input of other energy: 3% from original energy – lipids (triglycerides to adipose tissue), 7% - glucose (glycogen), 23% - conversion of saccharides to lipids, 23% - conversion of AA to proteins or glucose (glycogen).



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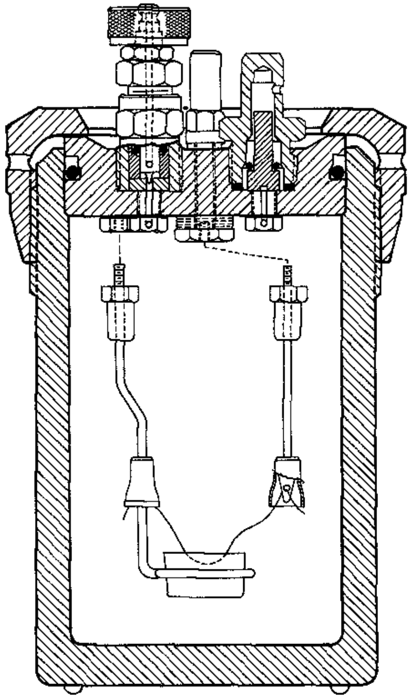
# Direct calorimetry

= measurement of energy released by burning of diet out of body (oxidation of compounds in a **calorimeter**)

1. Caloric bomb
2. Whole-body calorimeter (for laboratory animals, for humans)





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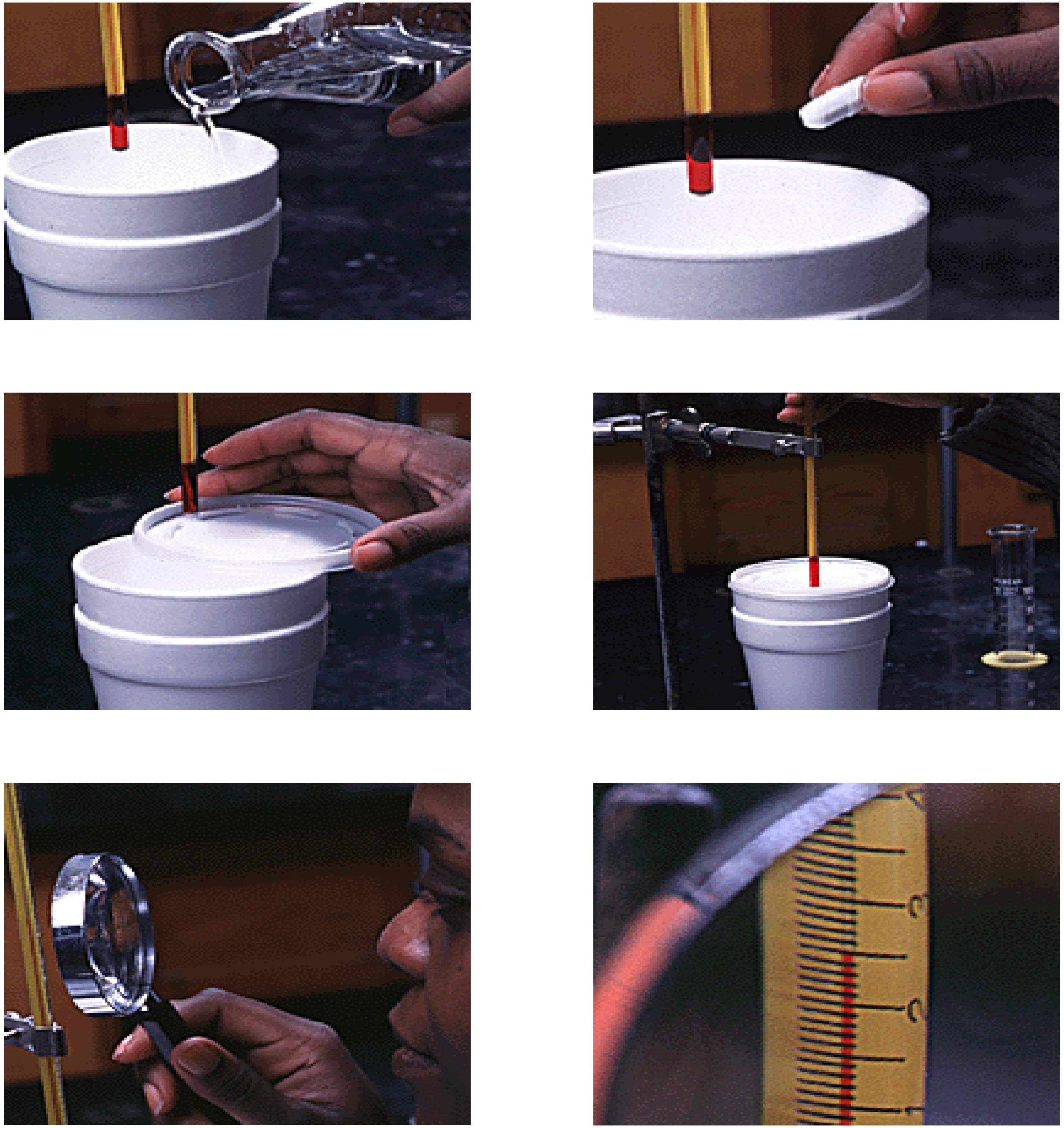



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# Indirect calorimetry

- Amount of consumed $O_2$.

- Amount of energy released for 1mol of consumed $O_2$; differs according to type of oxidized compound (the effect of diet composition)



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# Factors affecting (basal) metabolism

- Height, weight, **body surface**
- Gender
- Age
- Body temperature
- Emotional status
- High or low ambient temperature (the dependence is expressed as a **U** curve)
- Thyroidal status
- Plasmatic level of catecholamines
- Muscle work (before and/or during measurement)
- Food intake (before measurement)

# Work (physical activity, exercise)

Source: www.freepik.com. Photos created by freepik and standret



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# Skeletal muscle

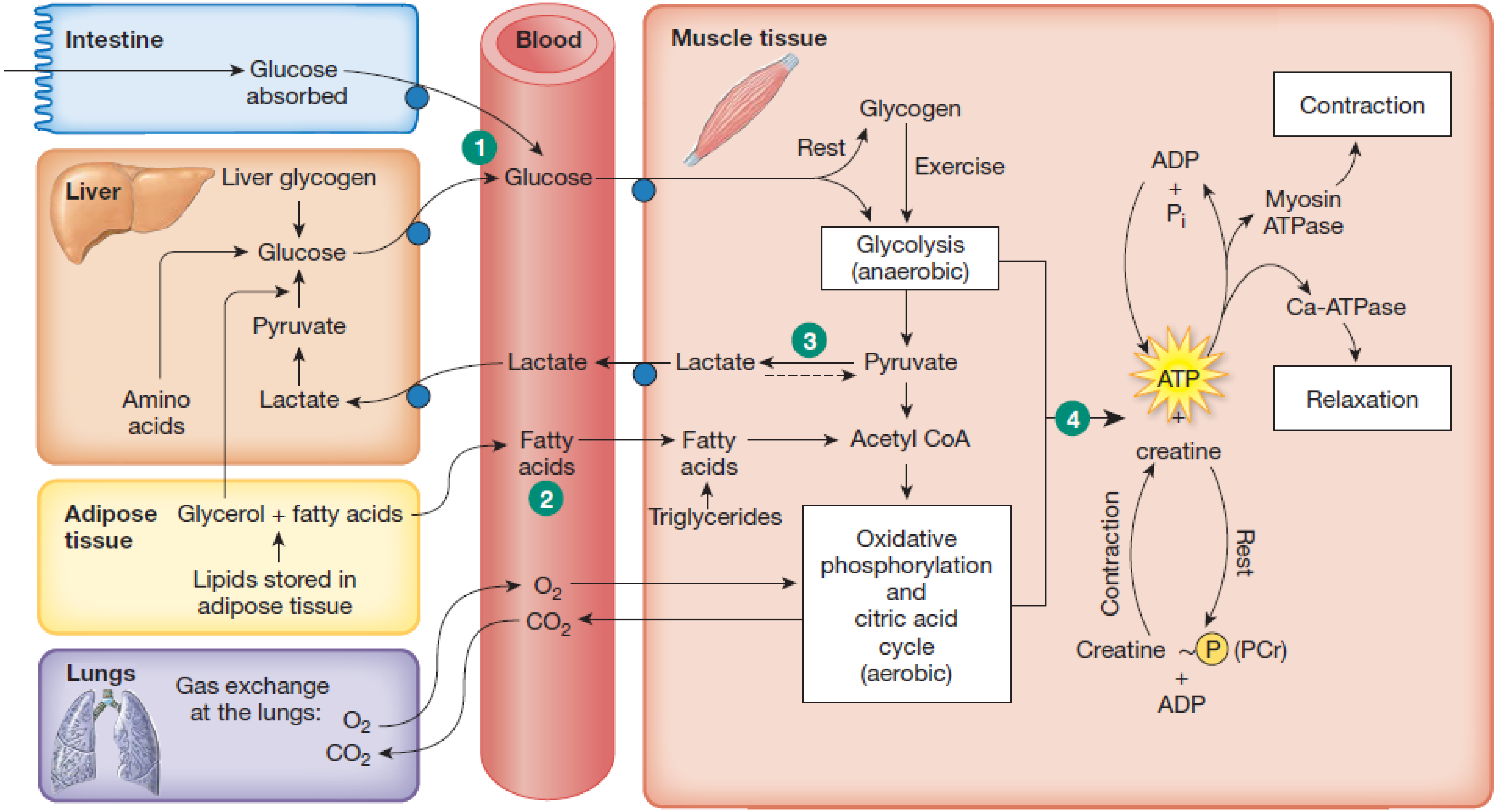
- Contraction: isometric (static work) *vs.* isotonic (dynamic work)

- Blood flow depends on muscle tension
- **Metabolic autoregulation**: ↓$pO_2$; ↑$pCO_2$; ↓pH; ↑$K^+$; ↑local temperature

- Metabolism: aerobic *vs.* anaerobic

- Muscle spindles – muscle tension – afferentation of exercise pressor reflex

# Skeletal muscle metabolism




Adopted from: D.U.Silverthorn: Human Physiology (An Integrated Approach)

# Reaction of the body to exercise

– Sympathetic NS (ergotropic system)

– Cardiovascular changes
– Respiratory changes
– Metabolic changes

– HOMEOSTASIS

# Anticipation of exercise

- Reaction of the body (cardiovascular system)
- Prepares the body for the increased metabolic turnover in the exercising skeletal muscles

- Similar to the early response to exercise
- Resembling fight-or-flight reaction

# Cardiovascular response to exercise

- Increased cardiac output
- **Redistribution of blood:**

*Vasoconstriction* in inactive skeletal muscles, the GIT, **skin**, (kidneys)

*Vasodilation* in active muscles (metabolic autoregulation)

- Increased venous return
- Histamine release
- Epinephrine release (adrenal medulla)
- Thermoregulation

# Increase of cardiac output. Cardiac reserve

- CO = SV x HR (SNS: positive inotropic and chronotropic effects)

- **Cardiac reserve = maximal CO / resting CO (4 – 7)**

- Coronary reserve = maximal CF / resting CF (~3.5)
- Chronotropic reserve = maximal HR / resting HR (3 – 5)
- Volume reserve = maximal SV / resting SV (~1.5)

*CO – cardiac output; CF – coronary flow; SV – stroke volume; HR – heart rate*



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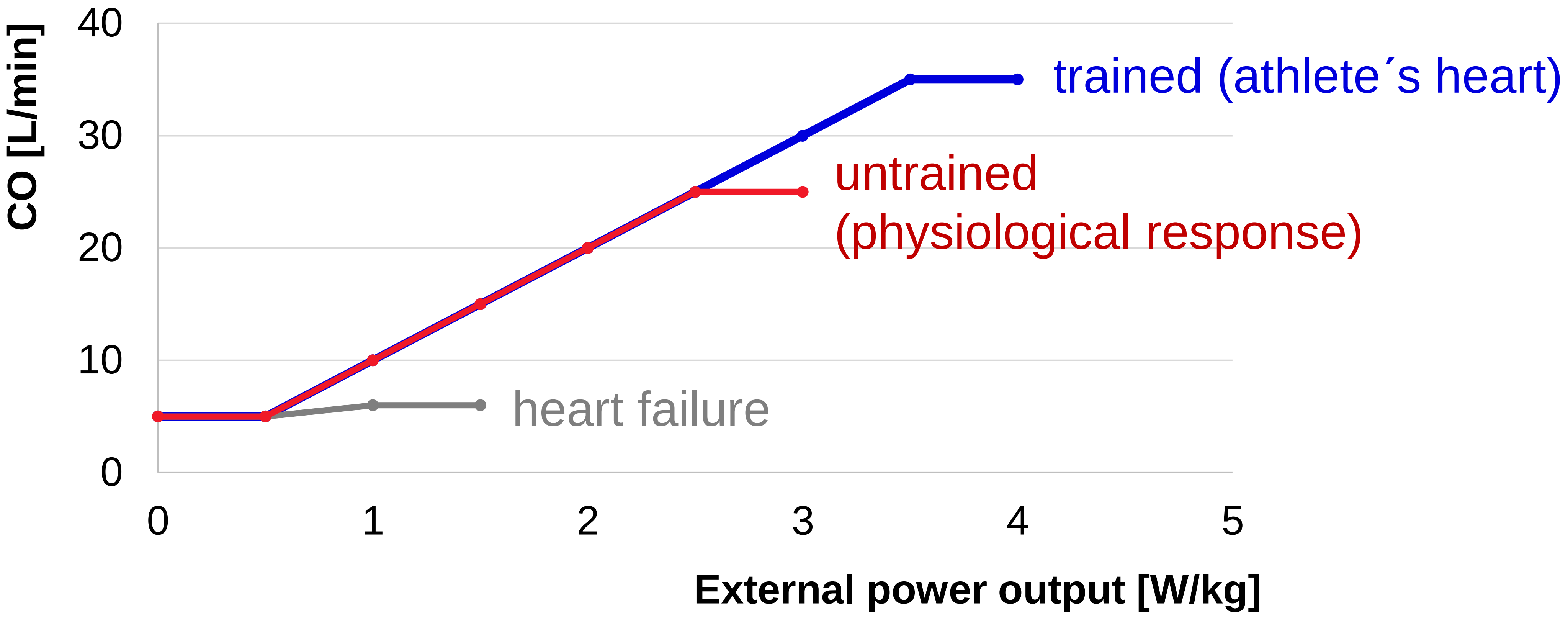
# Cardiac reserve in healthy and failing heart



# Changes of arterial blood pressure

| PARAMETER | AT REST | DURING EXERCISE | INCREASE (x) |
|---|---|---|---|
| **Cardiac output** [L/min] | 5 – 6 | 25 (35) | 4 – 5 (7) *cardiac reserve* |
| **Heart rate** [1/min] | (45) 60-90 | 190 – 200 (220) *age-dependent* | 3 – 5 *chronotropic reserve* |
| **Stroke volume** [mL] | 75 | 115 | ~1.5 *volume reserve* |
| **Systolic BP** [mmHg] | 120 | *static work* ↑ *dynamic work* ↑↑ | |
| **Diastolic BP** [mmHg] | 70 | *static work* ↑↑↑ *dynamic work* — / ↓ | |
| **Mean arterial P (MAP)** [mmHg] | ~90 | *static work* ↑ *dynamic work* — / ↑ | |
| **Muscle perfusion** [mL/min/100g] | 2 – 4 | 60 – 120 (180) *static vs. dynamic work* | 30 (10% $CO_{max}$) |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# Respiratory response to exercise

- Respiratory centre - ↑ ventilation
  - chemoreceptors: ↑ $pCO_2$ + ↓ pH
  - proprioceptors in lungs

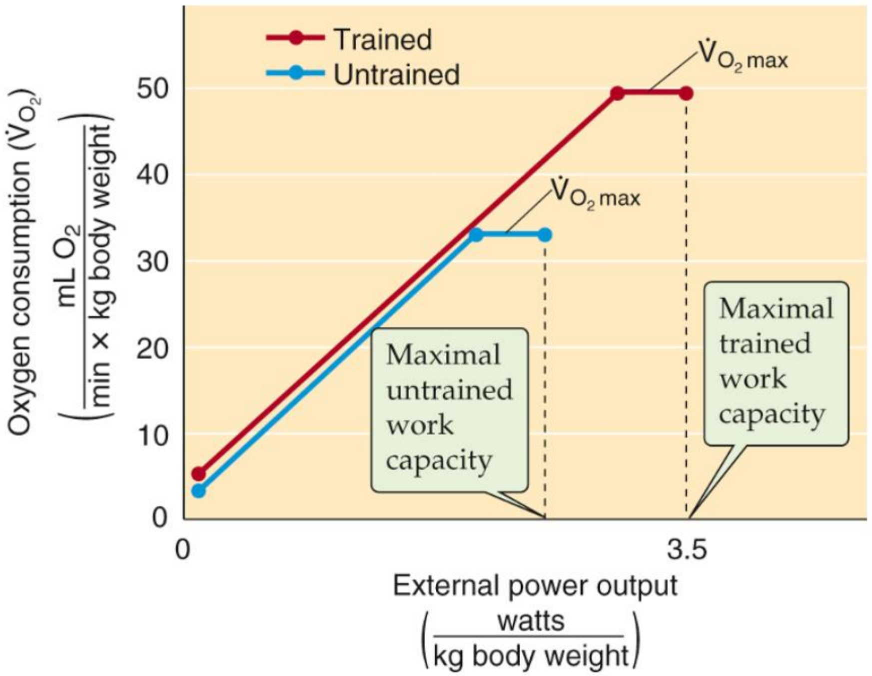
- Sympathetic stimulation (stress – anticipation)

# Respiratory response to exercise

| PARAMETER | AT REST | DURING EXERCISE | INCREASE (x) |
|---|---|---|---|
| **Ventilation** [L/min] | 6 – 12 | 90 – 120 | 15 – 20 *respiratory reserve* |
| **Breathing frequency** [1/min] | 12 – 16 | 40 – 60 | 4 – 5 |
| **Tidal volume ($V_T$)** [mL] | 0.5 – 0.75 | ~ 2 | 3 – 4 |
| **Pulmonary artery blood flow** [mL/min] | 5 – 6 | 25 – 35 | 4 – 6 |
| **$O_2$ uptake ($V_{O2}$)** [mL/min)] | 250 – 300 | ~ 3000 | 10 – 12 (25) |
| **$CO_2$ production** [mL/min] | ~ 200 | ~ 8000 | ~ 40 |

Adopted from: https://studentconsult.inkling.com/read/boron-medical-physiology-3e/chapter-60/figure-60-6

# Oxygen uptake by lungs




- Spiroergometry
- Resting $V_{O2}$: **~3.6** mL $O_2$ / (min x kg)
- **$V_{O2\ max}$** – objective index for aerobic power
  - untrained middle age person: **30 – 40** mL $O_2$ / (min x kg)
  - elite endurance athletes: **80 – 90** mL $O_2$ / (min x kg)
  - HF / COPD patients: **10 – 20** mL $O_2$ / (min x kg)

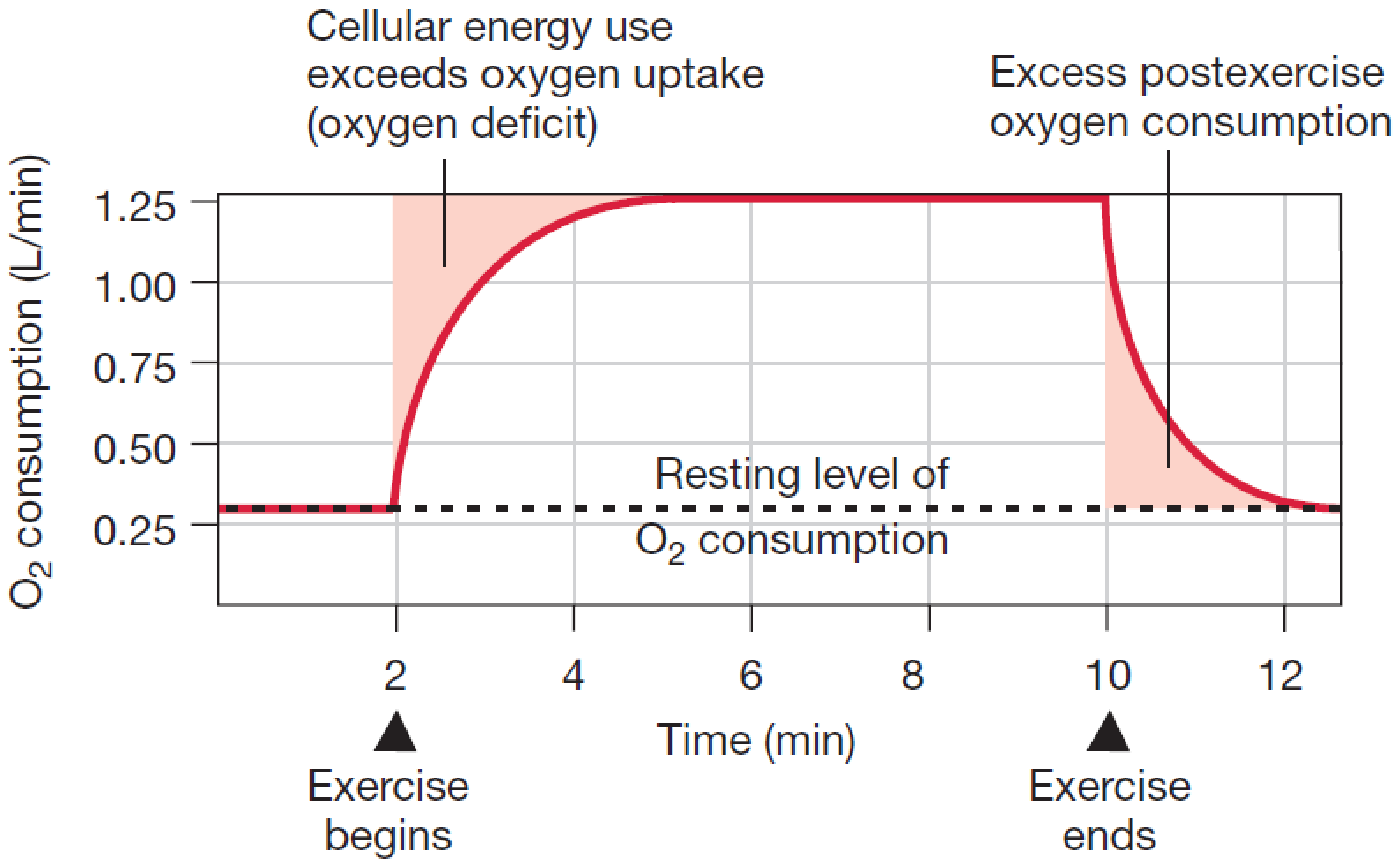
# Determinants of $V_{O2\ max}$

1. Uptake of $O_2$ by the lungs
   – pulmonary ventilation
2. $O_2$ delivery to the muscles
   – blood flow (pressure gradient – cardiac output x resistance)
   – hemoglobin concentration
3. Extraction of $O_2$ from blood by muscle
   – $pO_2$ gradient: blood - mitochondria

# Oxygen consumption during exercise

Adopted from: D.U.Silverthorn: Human Physiology (An Integrated Approach)

– Oxygen debt



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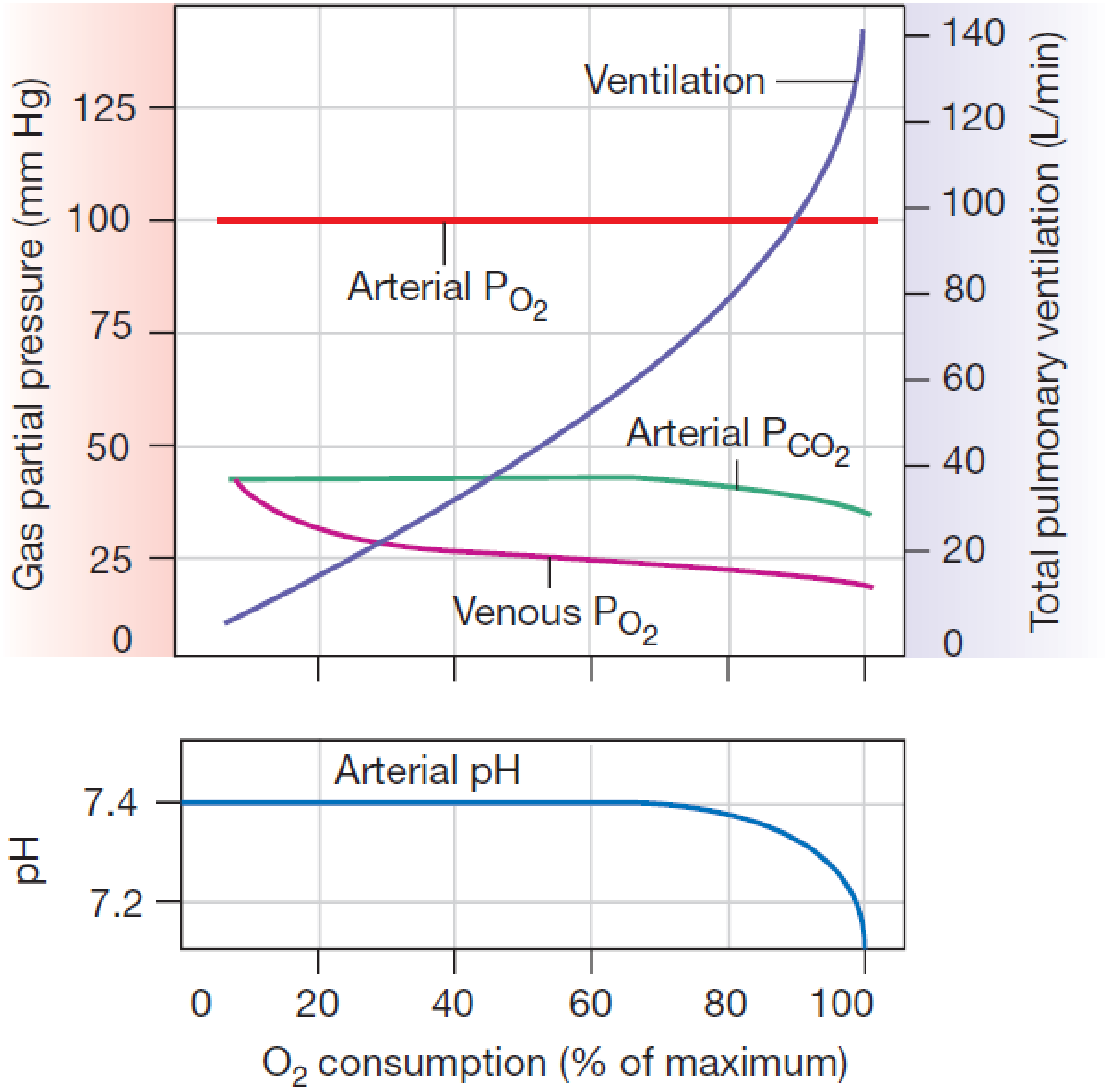
# Blood gases during exercise

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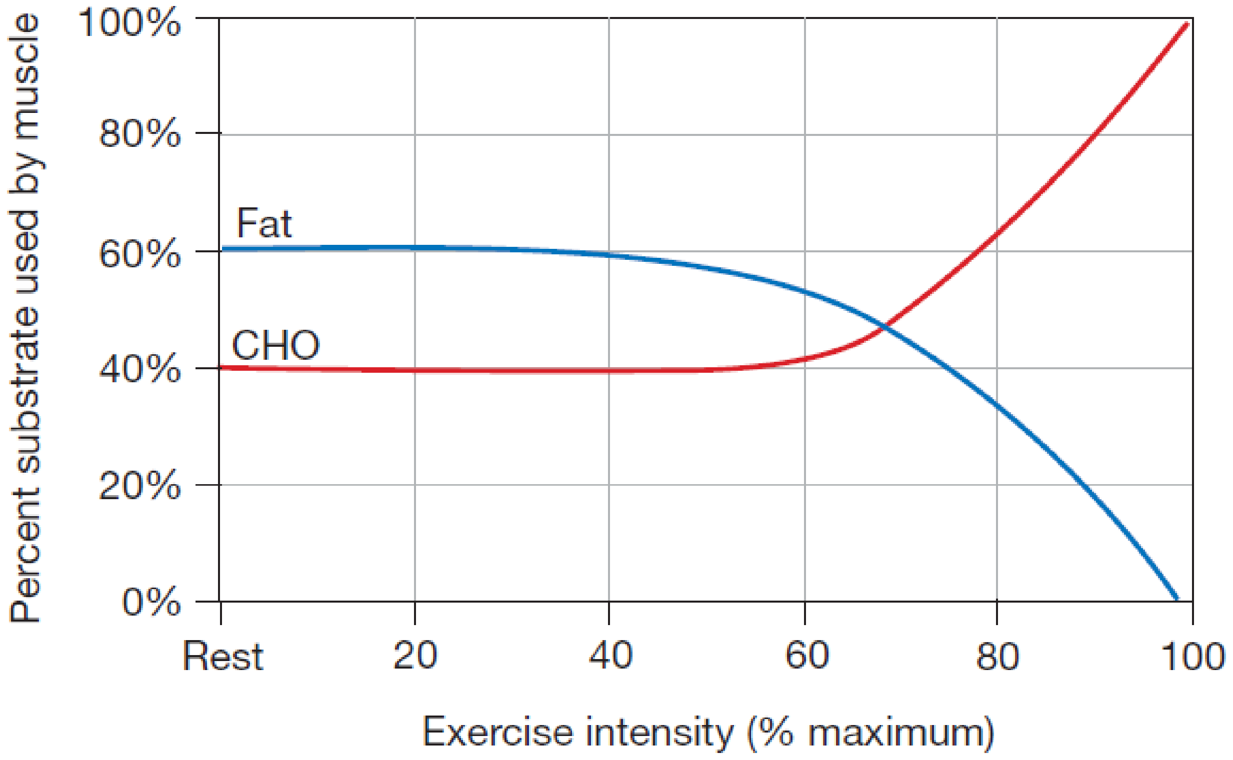
# Energy substrates used by skeletal muscle during exercise

- Low-intensity e.: fats
- High-intensity e.: glucose




Data from G. A. Brooks and J. Mercier, *J App Physiol* 76: 2253–2261, 1994

Adopted from: D.U.Silverthorn: Human Physiology (An Integrated Approach)





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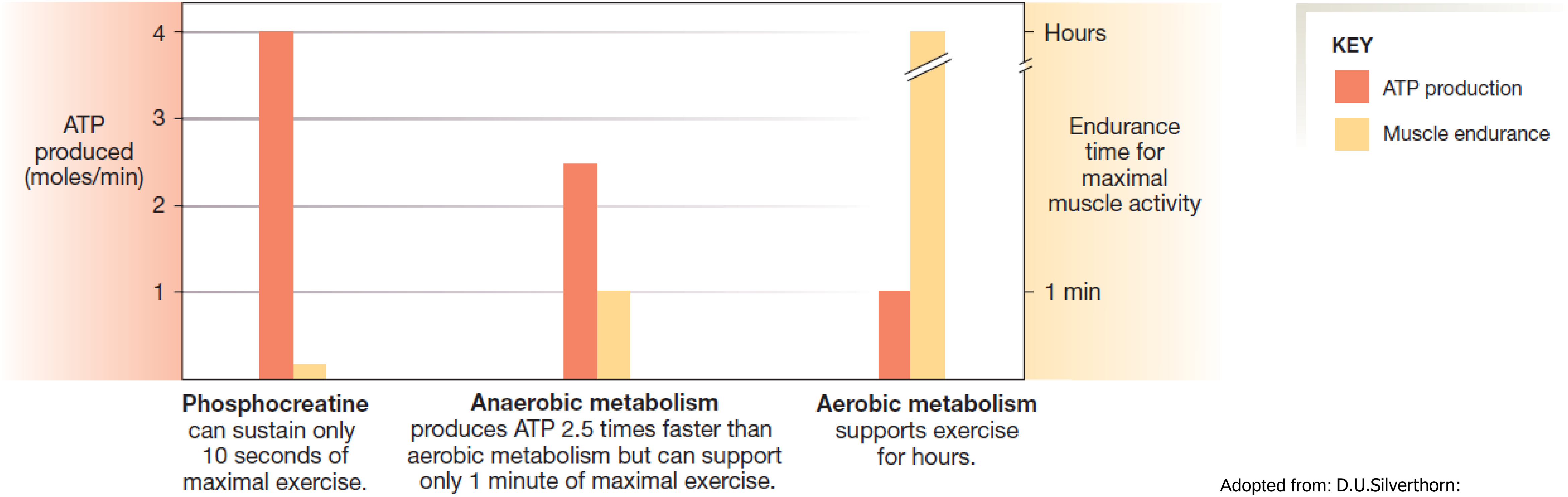
# Energy substrate use – aerobic *vs.* anaerobic

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# Testing of fitness

- Spiroergometry
- Standardised workload
  - exactly: in W/kg
  - comparative (simple, inaccurate): in MET
    - metabolic equivalent (actual MR / resting MR)
    - 1 MET = uptake of 3.5 ml $O_2$/kg.min ≈ 4.31 kJ/kg.h
    - sleeping ≈ 0.9 MET; slow walking ≈ 3-4 MET; fast running ≈ 16 MET

# Indexes of fitness

- $W_{170}$ [W/kg]
- $V_{O_2\,max}$ [mL $O_2$ / (min x kg)]
- Aerobic / anaerobic threshold

- Fatigue
- Training
- Adaptation to exercise