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Introduction to Biophysical Aspects of Human Movement (APA-1161)

Exercise physiology (O_2 consumption)
December 4, 2012




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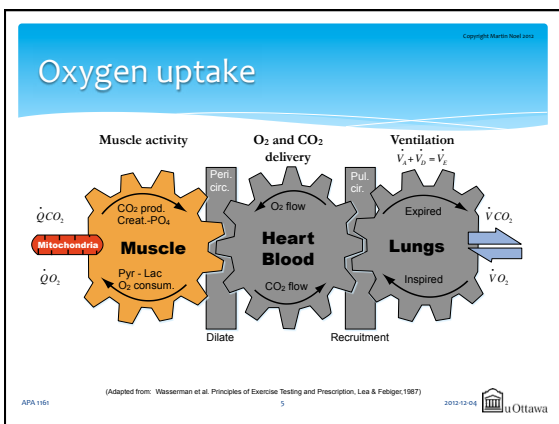
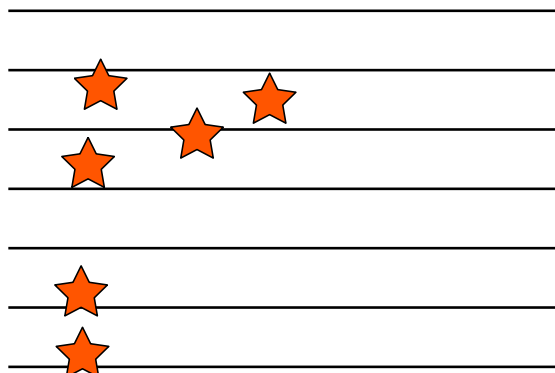
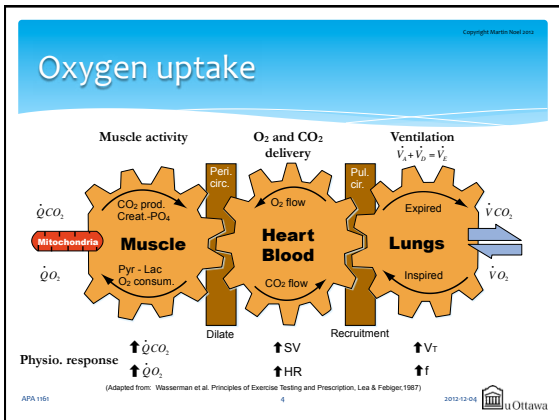
TODAY



Lesson Plan

- Overview of O_2 uptake
- Cardiac output (Fick)
- A- VO_2 difference
- Measurement of VO_2
 - Direct
 - Indirect
- Principle of ex. testing
- Categorisation of exercise capacity

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Fick's equation

- Fick
- Cardiac output
- a-VO₂ difference

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Fick, a little history !




- Adolf Fick
 - Cardiovascular physiologist
 - 1870's
 - Developed formula that allowed the rate of oxygen consumption to be determined if the cardiac output and the arterial-venous difference were known

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Fick's equation

$$\dot{V}O_2 = \dot{Q} \times \Delta a - \bar{V}O_2$$




 Heart rate Stroke volume

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Cardiac output

- Cardiac output**
 - Volume of blood pumped by the heart per minute (mL blood/min)
 - Reflects the functional capacity of the cardiovascular system
 - Heart rate x stroke volume
- Cardiac index**
 - Cardiac output of a person referenced to their body surface (l/min/m²)
- Stroke volume**
 - Volume of blood ejected by each contraction



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Cardiac output
(Assessment-Echocardiography)

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Cardiac output
(Assessment-Echocardiography)

Left Parasternal Long
Parasternal Long

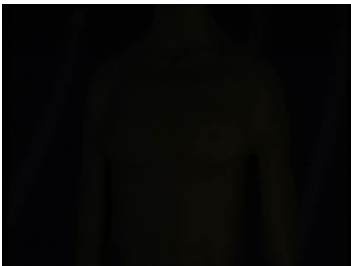
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Cardiac output
(Assessment-Echocardiography)

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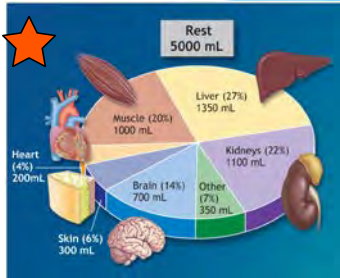
Cardiac output (Assessment-others)



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Cardiac output (Distribution - Rest)

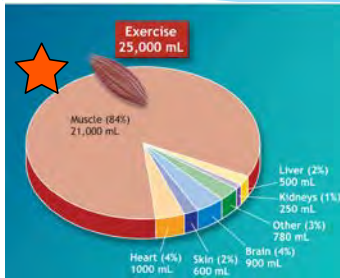


- 5 L (average males)
 - An average heart rate of 70 bpm and an average stroke volume of 71.4 mL
- 4 L (average females)
 - An average heart rate of 70 bpm and an average stroke volume of 50-60 mL

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Cardiac output (Distribution - Exercise)

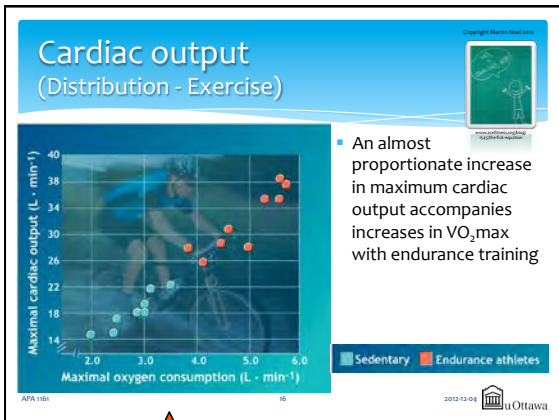


- CO increases rapidly during the transition from rest to steady-rate exercise
- Then rises gradually until it plateaus when blood flow meets the exercise metabolic requirements

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Cardiac output (Quiz)

Cardiac output is a product of which of the following variables?

- Heart rate and a-vO₂ difference
- Stroke volume and heart rate
- Heart rate and blood flow
- V-O₂max and heart rate

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Cardiac output (Quiz)

Endurance athletes achieve higher cardiac outputs through large increases in which variable of the cardiac output formula?

- Stroke volume
- Heart rate
- VO₂max
- Blood pressure

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Fick's equation

$$\dot{V}O_2 = \dot{Q} \times \Delta a - \bar{V}O_2$$

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a-VO₂ difference

Oxygen extraction during rest

- During rest there is an a-VO₂ difference of 5 mL of oxygen per deciliter of blood perfusing the tissue-capillary bed
- 15 mL of oxygen or 75% of the blood's original oxygen load still remains bound to hemoglobin

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a-VO₂ difference

Oxygen extraction during exercise



- During maximum exercise Hb releases a considerable quantity of its "reserve" oxygen from blood that perfuses active tissues
- Exercise oxygen consumption increases by:
 - Increased cardiac output
 - Expanded a-VO₂ difference

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a-VO₂ difference
(Factor of influence)





Factors of influence

- Central and peripheral factors interact to increase oxygen extraction in active tissue during exercise:
 - A large portion of the cardiac output is diverted to active tissue
 - Some tissues temporarily decrease their blood supply to make more oxygen available
 - Exercise training redirects a greater portion of the central circulation to active muscle

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a-VO₂ difference
(Factor of influence)



Factors of influence

- Central and peripheral factors interact to increase oxygen extraction in active tissue during exercise:
 - An increase in skeletal muscle microcirculation
 - An increased capillary-to-fiber ratio
 - An increase in the size and number of mitochondria
 - Augmenting aerobic enzyme activity
 - Local vascular and metabolic improvements within muscle enhance its capacity to produce ATP aerobically

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a-VO₂ difference
(Factor of influence)

Upper vs lower extremities


Factors of influence

- The highest oxygen consumption during arm exercise averages 20 to 30% lower than leg exercise
- Arm exercise produces lower maximal values for heart rate and pulmonary ventilation
- These differences relate to the relatively smaller muscle mass activated in arm exercise

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a-VO₂ difference (Quiz)



How does oxygen consumption during submaximal exercise compare for arms and legs?


- a) Arms have a higher VO_{2,max}
- b) Legs have a higher VO_{2,max}
- c) They are the same
- d) They can't be compared

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Measurement of VO₂



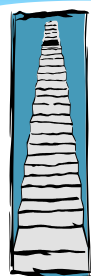


- Direct
- Indirect
- Prediction

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Measurement of VO₂



- Direct measurement
 - MIR, Mass spectroscopy
- Indirect measurement
 - Calorimetry
 - Open and closed circuit
- Estimated measurement
 - Astran, Leger-Lambert

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Measurement of VO_2
(Direct measurement)

Magnetic Resonance Imaging (MRI)

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Measurement of VO_2
(Direct measurement)

Mass spectrometry

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Measurement of VO_2
(Calorimetry)

Metabolic Processes

$Food + O_2 \rightarrow CO_2 + H_2O + Heat$

Calorimetry

Direct Heat Measurement

O₂ consumption, CO₂ production and N₂ balance

- All of the body's metabolic processes result in heat production
- The calorie is the basic unit of heat measurement
- Calorimetry defines the measurement of heat transfer
 - Direct calorimetry
 - Indirect calorimetry

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Measurement of VO₂ (Direct calorimetry)

Direct calorimetry

- Directly measures energy expenditure during rest and physical activity
- Has considerable theoretical implications but limited practical applications in humans
- Accurate measurements of heat production in the calorimeter require considerable time and expense and formidable engineering expertise
- Calorimeters remain inapplicable for energy determinations for most sport, occupational, and recreational activities

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Measurement of VO₂ (Indirect calorimetry)

Indirect calorimetry

- All energy-releasing reactions in humans depend on oxygen use so measuring oxygen consumption during physical activities provides an indirect yet accurate estimate of energy expenditure
- Is simpler and less expensive
- Yields results comparable to direct measurement in the human calorimeter
- Two types:
 - Closed-circuit spirometry
 - Open-circuit spirometry

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Measurement of VO₂ (Indirect calorimetry)


Indirect calorimetry

- Closed-circuit spirometry
 - Simple method and is able to directly measure O₂ consumption but has limited practical applications

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Measurement of VO_2
(Indirect calorimetry)


- Indirect calorimetry
 - Closed-circuit spirometry



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Measurement of VO_2
(Indirect calorimetry)


- Indirect calorimetry
 - Open-circuit spirometry
 - Provides a relatively simple, practical way to measure O_2 consumption and infer energy expenditure
 - Procedure:
 - Subject inhales ambient air with a constant composition (20.93% O_2 , 0.03% CO_2 , 79.04% nitrogen)
 - Changes in O_2 and CO_2 % in expired air compared with the % in inspired ambient air indirectly reflect the ongoing process of energy metabolism
 - Types:
 - Bag technique
 - Portable spirometry
 - Computerized instrumentation



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Measurement of VO_2
(Indirect calorimetry)

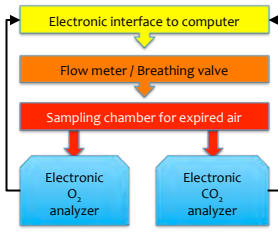
- Indirect calorimetry
 - Open-circuit spirometry
 - Douglas's Bag, Claude G. Douglas (1882-1963)



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Measurement of VO_2 (Indirect calorimetry)

- Indirect calorimetry
 - Closed-circuit spirometry




```
graph TD; A[Electronic interface to computer] --> B[Flow meter / Breathing valve]; B --> C[Sampling chamber for expired air]; C --> D[Electronic O2 analyzer]; C --> E[Electronic CO2 analyzer]; D --> A; E --> A;
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Measurement of VO_2 (Indirect calorimetry)

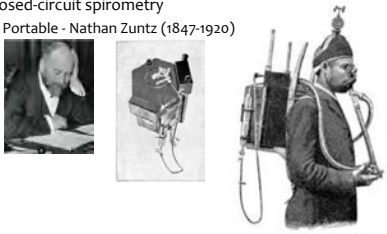
- Indirect calorimetry
 - Closed-circuit spirometry



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Measurement of VO_2 (Indirect calorimetry)



- Indirect calorimetry
 - Closed-circuit spirometry
 - Portable - Nathan Zuntz (1847-1920)




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Measurement of VO₂
(Indirect calorimetry)

- Indirect calorimetry
 - Closed-circuit spirometry
 - Portable – Today!



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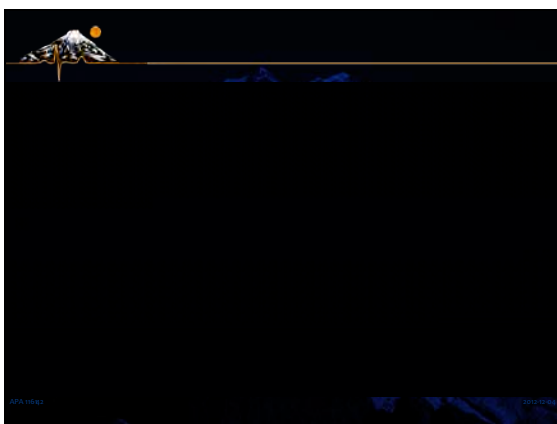
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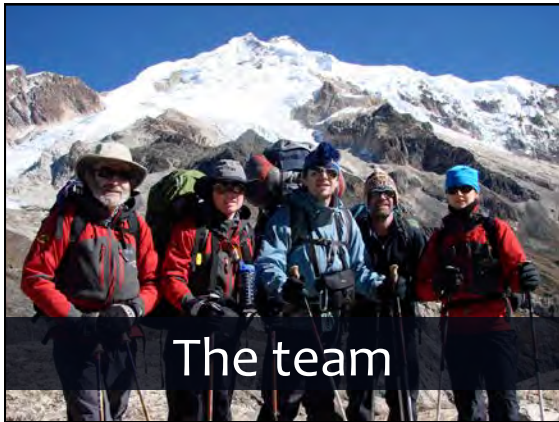
Huayna Potosi 2006

Cuando la pasión del saber encuentra el amor de la montaña

ATMOSPHERE
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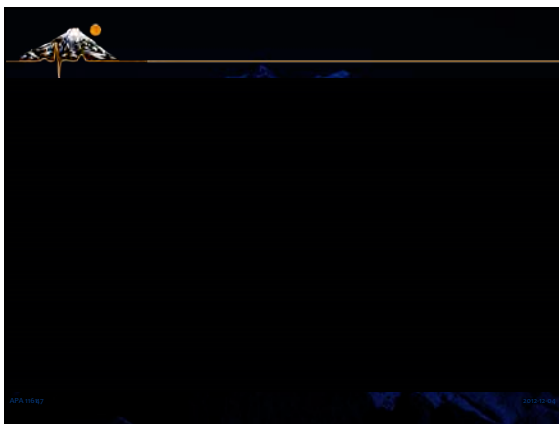






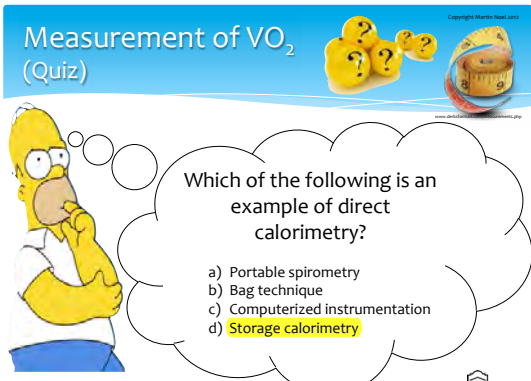
- Camps #1
 - Le Relais - 353m
- Camps #2
 - La Paz - 4 000m
- Camps #3
 - Le refuge - 4 750m
- Camps #4
 - Campo de Roca - 5 300m







Measurement of VO₂
(Quiz)

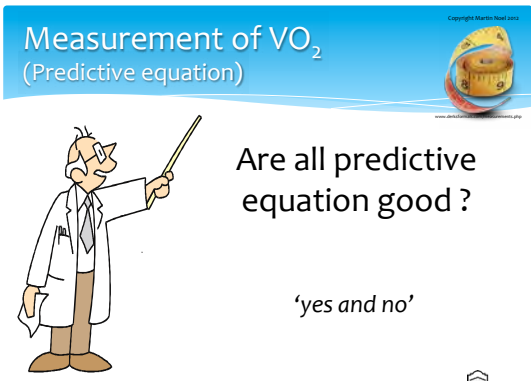


Which of the following is an example of direct calorimetry?

- a) Portable spirometry
- b) Bag technique
- c) Computerized instrumentation
- d) **Storage calorimetry**

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Measurement of VO₂
(Predictive equation)

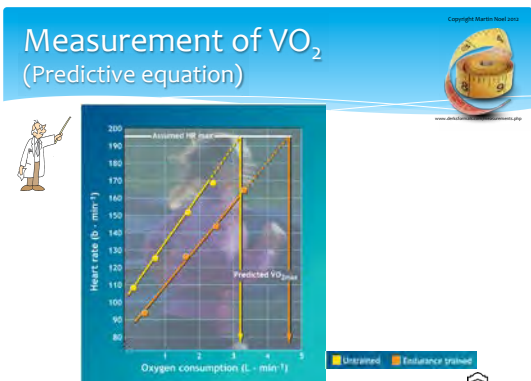


Are all predictive equation good ?

'yes and no'

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Measurement of VO₂
(Predictive equation)



Heart rate (b · min⁻¹)

Oxygen consumption (L · min⁻¹)

Untrained Endurance trained

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Measurement of VO₂
(Predictive equation)

Walk 1,9-3,7 mph

$$VO_2 \text{ (mLO}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = (0,1 \cdot S) + (1,8 \cdot S \cdot G) + 3,5$$

Gross consumption = \rightarrow + \uparrow + \rightarrow

Flat at 3,4 mph:
 * $3,4 \cdot 26,8 = 91,12 \text{ m} \cdot \text{min}^{-1}$
 $= [0,1(91,12)] + [1,8(91,12) \cdot 0,0] + (3,5)$
 $= 9,112 + 0 + 3,5$
 $= 12,61 \text{ mLO}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$

S = speed (m · min⁻¹)
 M = Body mass (kg)
 f = Step rhythm (min⁻¹)
 G = Grade (% in decimal)
 W = power (watts)
 H = Height of step (m)

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Measurement of VO₂
(Predictive equation)

Running <5 mph

$$VO_2 \text{ (mLO}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = (0,2 \cdot S) + (1,8 \cdot S \cdot G) + 3,5$$

Gross consumption = \rightarrow + \uparrow + \rightarrow

at a slope of 10%
 $= [0,2 \times (5 \times 26,8)] + [0,9 \times (5 \times 26,8) \times 0,1] + (3,5)$
 $= 26,8 + 12,06 + 3,5$
 $= 42,36 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$

S = speed (m · min⁻¹)
 M = Body mass (kg)
 f = Step rhythm (min⁻¹)
 G = Grade (% in decimal)
 W = power (watts)
 H = Height of step (m)

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Measurement of VO₂
(Predictive equation)

Ergocycle

$$VO_2 \text{ (mLO}_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = (10,8 \cdot W \cdot M^{-1}) + 3,5$$


Power 100 W et Body mass 65 kg:
 $= (10,8 \cdot 100 \cdot 65^{-1}) + (7)$
 $= 23,6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$

S = speed (m · min⁻¹)
 M = Body mass (kg)
 f = Step rhythm (min⁻¹)
 G = Grade (% in decimal)
 W = power (watts)
 H = Height of step (m)

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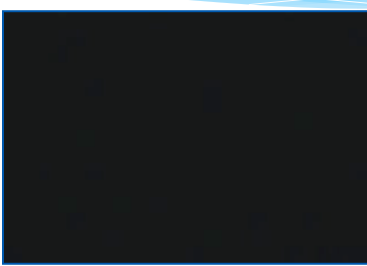

Principle of exercise testing



- VO₂max / peak
- Ventilation
- RQ / RER
- BP
- Maximum

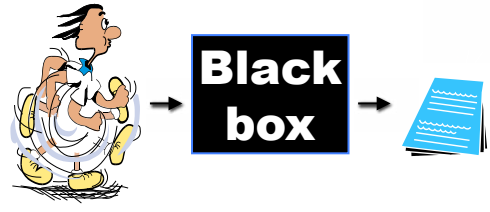

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Principle of exercise testing



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Principle of exercise testing



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Principle of exercise testing

- Rate of oxygen consumption
 - V = volume; O₂ = Oxygen; • = rate
 - mL O₂ · min⁻¹ or L O₂ · min⁻¹
 - Energy cost of activities not involving body mass
 - mL O₂ · kg⁻¹ · min⁻¹
 - Comparison of persons of different weight
 - Energy cost of activity involving body mass

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Principle of exercise testing

- In general

Speed (km · h ⁻¹)	4.8	8.0	11.2	11.2	11.2	11.2	11.2
Time (min)	0-2	2-4	4-6	6-8	8-10	10-12	12-14
Treadmill grade (%)	0	5.5	7.5	9.5	11.5	13.5	15.5

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Principle of exercise testing

- Max vs peak ?

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■ **Step vs peak ?**

Workload

Time

Step Ramp

★

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■ **Step vs peak ?**

J Am Coll Cardiol. 1991 May;17(6):1334-42.

Comparison of the ramp versus standard exercise protocols.

Myers J, Buchanan N, Walsh D, Kraemer M, McAuley P, Hamilton-Wessler M, Froelicher VF.

Cardiology Section, Long Beach Veterans Affairs Medical Center, California 90822.

To compare the hemodynamic and gas exchange responses of ramp treadmill and cycle ergometer tests with standard exercise protocols used clinically, 10 patients with chronic heart failure, 10 with coronary artery disease who were asymptomatic during exercise, 11 with coronary artery disease who were limited by angina during exercise and 10 age matched normal subjects performed maximal exercise using six different exercise protocols. Gas exchange data were collected continuously during each of the following protocols, performed on separate days in randomized order: Bruce, Balke and an individualized ramp treadmill; 35 Wlstage, 50 Wlstage and an individualized ramp cycle ergometer test. Maximal oxygen uptake was 66% greater on the treadmill protocols combined (2.14 ± 0.8 ml/kg per min) versus the cycle ergometer protocols combined (0.8 ± 0.7 ml/kg per min) (p less than 0.001), although no differences were observed in maximal heart rate (175 ± 24 versus 184 ± 24 beats/min for the treadmill and cycle ergometer protocols, respectively). No major differences were observed in maximal heart rate or maximal oxygen uptake among the various treadmill protocols or among the various cycle ergometer protocols. The ratio of oxygen uptake to work rate, expressed as a slope, was highest for the ramp tests (slope ± SE ml/kg per min = 0.80 ± 0.15 and 0.78 ± 0.17 for ramp treadmill and ramp cycle ergometer, respectively). The slopes were poorest for the tests with the largest increments in work (0.62 ± 0.40 and 0.59 ± 0.28 for the Bruce treadmill and 50 Wlstage cycle ergometer, respectively). (ABSTRACT TRUNCATED AT 250 WORDS)

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Principle of exercise testing

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(Interpretation)

■ **V_E (ventilation / min.)**

- = Breathing frequency • Tidal volume
- = 12 • 0,5 L
- = 6 L • min⁻¹

	Breathing rate (Breathings•min ⁻¹)	Tidal volume (L•ventilation ⁻¹)	VE (L•min ⁻¹)
Rest	12	0,5	6
Moderate ex.	30	2,5	75
Vigourous ex.	50	3,0	150

■ **MVV (maximal voluntary ventilation)**

- = 37,5 • FVC
- * MVV (25%) < VEmax
- ** MPOC - VEmax normal = 40% MVV

	MVV (L • min ⁻¹)
Male (□) 30 ans	140-180
Female (□) 30 ans	80-120
Athlete (Cross-country skiing)	192
Max. measured	239

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Principle of exercise testing (Interpretation)

- Respiratory quotient**
 - RQ = CO₂ produced ÷ O₂ consumed
 - Carbohydrate, fat, and protein require different amounts of O₂ for complete oxidation of each molecule's carbon and hydrogen atoms to the CO₂ and water end products
 - Provides a convenient guide to approximate the nutrient mixture catabolized for energy during rest and aerobic exercise

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Principle of exercise testing (Interpretation)

- Respiratory quotient**
 - Carbohydrate**
 - $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
 - RQ = 6 CO₂ / 6 O₂ = 1
 - Because gas exchange during glucose oxidation produces a number of CO₂ molecules equal to the number of O₂ molecules consumed
 - RQ = 1
 - Protein**
 - $C_8H_{16}O_2 + 23 O_2 \rightarrow 16 CO_2 + 16 H_2O$
 - QR = 16 CO₂ / 23 O₂ = 0,818 (0,8)
 - Because proteins require more oxygen in relation to carbon
 - RQ=0,82
 - Fat**
 - $C_{27}H_{54}O_2 + 77 O_2 \rightarrow 63 CO_2 + 38 H_2O + SO_2 + 9 CO(NH_2)_2$
 - QR = 63 CO₂ / 77 O₂ = 0,696 (0,7)
 - Because fat catabolism requires more O₂ in relation to CO₂ production
 - RQ=0,70

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Principle of exercise testing (Interpretation)


Exercise duration (h)	RQ	Carbohydrate %	Fat %
Start	1.0	20	80
1	0.95	25	75
2	0.9	30	70
3	0.85	35	65
4	0.8	40	60
5	0.75	45	55
6	0.75	50	50

- Respiratory quotient**
 - Carbohydrate : RQ = 1
 - Protein : RQ=0,82
 - Fat : RQ=0,70

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Principle of exercise testing (Interpretation)

- Respiratory Exchange Ratio (RER)**
 - Is computed in the same manner as RQ
 - Reflects the ratio of CO₂ produced to O₂ consumed when factors other than food combustion alter the exchange of O₂ and CO₂ in the lungs and the ratio of gas exchange no longer reflects only the substrate mixture of energy metabolism
 - Strongly associated with exercise intensity

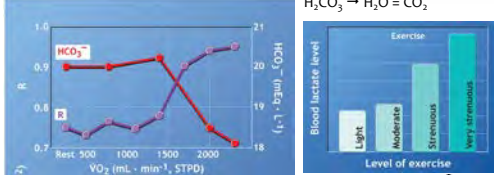
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Principle of exercise testing (Interpretation)


- Respiratory Exchange Ratio (RER)**

$$\frac{\text{Production of carbon dioxide}}{\text{Oxygen consumption}} = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} = \text{RER}$$

RER > 1.00
HLa + NaHCO3 -> NaLa + H2CO3 -> H2O + CO2

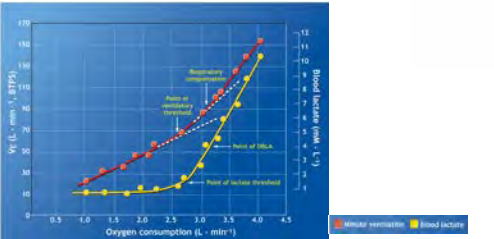


The graph shows RER increasing from ~0.8 at rest to ~1.0 at 1500 ml/min O₂ consumption, then rising above 1.0. The bar chart shows blood lactate levels increasing from ~18 mg/dl at rest to ~21 mg/dl at very strenuous exercise.


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Principle of exercise testing (Interpretation)

- Lactate threshold**



The graph plots oxygen consumption (L·min⁻¹) on the x-axis and blood lactate level (mmol·L⁻¹) on the y-axis. It shows a curve for blood lactate that rises exponentially after a certain point, and a curve for oxygen consumption that rises linearly. Key points marked include the 'Point of lactate threshold', 'Point of OBLX', and 'Anaerobic threshold'.

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Principle of exercise testing (Interpretation)

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Blood pressure

Figure 3: Normal response to progressive treadmill exercise in healthy subjects. Note the normal rise in heart rate and systolic blood pressure with increasing workload. (Reprinted with permission from Donald W. Fitts and the Board of Directors, American College of Sports Medicine, Champaign, IL. Copyright American College of Sports Medicine, 2007-2012)

Fletcher et al. (2011) Circulation, 124:1694-1700

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Principle of exercise testing (Interpretation)

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Criteria for stopping test

- Patient's request (to stop)
- Suspicion of a myocardial infarction or acute myocardial infarction (heart attack)
- Onset of moderate-to-severe angina (chest pain)
- Drop in systolic blood pressure (SBP) below standing resting pressure or drop in SBP with increasing workload accompanied by signs or symptoms
- Signs of poor perfusion (circulation or blood flow), including pallor (pale appearance to the skin), cyanosis (bluish discoloration), or cold and clammy skin
- Severe or unusual shortness of breath
- CNS (central nervous system) symptoms
 - e.g., ataxia (failure of muscular coordination), vertigo (An illusion of dizzying movement), visual or gait (pattern of walking or running) problems, confusion)
- Serious arrhythmias (abnormal heart rhythms)
 - e.g.: second / third degree AV block, atrial fibrillation with fast ventricular response, increasing premature ventricular contractions or sustained ventricular tachycardia)
- Technical inability to monitor the ECG

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Principle of exercise testing (Interpretation)

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Achieved maximum ?

- Plateau of $\dot{V}O_2$
- Plateau of HR
- RER >1.10
- Exercise perception >8/10

1 - 10 Borg Rating of Perceived Exertion Scale	
0	Rest
1	Really Easy
2	Easy
3	Moderate
4	Not too hard
5	Hard
6	
7	Really Hard
8	
9	Very, Very Hard
10	Very, Very, Very Hard

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Cardio vascular fitness

FITNESS ■ Calorimetry
 Direct
 Indirect

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Maximal oxygen consumption (L · min⁻¹)

Age (y)

Active males
 Sedentary males

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FITNESS


TABLE 11.4 ■ Estimated Genetic Contribution to Individual Differences in Important Components of Health-Related Physical Fitness

Fitness Component	Genetic Contribution
VO _{2max}	20–30%
Submaximal exercise response	20–30%
Muscular fitness	20–50%
Blood lipid profile	30–50%
Resting blood pressure	30%
Total body fat	25%
Regional fat distribution	30%
Habitual activity level	30%

Modified from Reschard C, Drouot L. Heritability, activity level, fitness, and health. In: Physical activity, fitness, and health. Champaign, IL: Human Kinetics, 1994.


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Cardiovascular Fitness Classifications						
Gender	Age	Poor	Fair	Average	Good	Excellent
Men	<29	<24.9	25-33.9	34-43.9	44-52.9	≥53
	30-39	<22.9	23-30.9	31-41.9	42-49.9	≥50
	40-49	<19.9	20-26.9	27-36.9	37-44.9	≥45
	50-59	<17.9	18-24.9	25-33.9	34-42.9	≥43
Women	60-69	<15.9	16-22.9	23-33.9	34-40.9	≥41
	<29	<23.9	24-30.9	31-38.9	39-48.9	≥49
	30-39	<21.9	22-27.9	28-36.9	37-44.9	≥45
	40-49	<16.9	17-24.9	25-34.9	35-41.9	≥42
	50-59	<14.9	15-21.9	22-31.9	32-39.9	≥40
60-69	<12.9	13-20.9	21-32.9	33-39.9	≥37	


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Men




Maximal oxygen consumption (mL · kg⁻¹ · min⁻¹)

Women

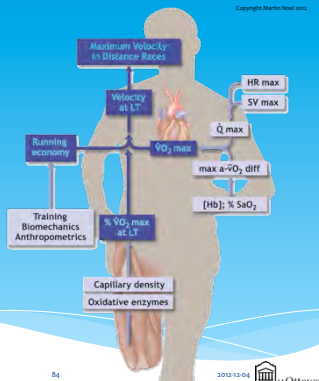


Maximal oxygen consumption (mL · kg⁻¹ · min⁻¹)

★

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Take home message



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