Oxygen Transport in Exercise

Prof. Dr. Alfred Hager

Department of Pediatric Cardiology and Congenital Heart Disease
Head of Outpatient Section
Head of Exercise Laboratory
Member of DGPK Guideline Committee
Conflicts of Interests

Institutional
• Contribution to clinical trials: Actelion, Medtronic, Edwards, Occlutech, Novartis, Lilly
• Unrestricted grants for investigator initiated trials: Pfizer, GlaxoSmithKline, Abbott, Actelion

Private
• Shareholder: Celgen, Gilead, Vertex, Abbvie, Pfizer, Novartis, Johnson & Johnson, Amgen, Cerner, Lilly, Baxter, Merck, Biogen, …
• Advisory board reimbursement: Actelion
• Speakers reimbursement: Schiller, Actelion, Abbott, Pfizer, Encysive, AOP Orphan, OMT, GlaxoSmithKline, Medtronic
• Travel expense reimbursement: Pfizer, GlaxoSmithKline, AOP Orphan Pharmaceuticals, Lilly, Actelion, Medtronic, Arrows, Guidant, Fresenius
Oxygen Transport

ventilation
diffusion
lung perfusion
heart
muscle perfusion
diffusion
metabolism

\( O_2 \) \hspace{2cm} \( CO_2 \)

Mito.
Fick’s Principle

\[ \text{flow} = \frac{\text{indicator uptake}}{\text{concentration change}} \]

\[ \text{blood flow}_{\text{pulmonary}} = \frac{\text{oxygen uptake}}{\left(\text{C}_{\text{pv}}\text{O}_2 - \text{C}_{\text{pa}}\text{O}_2\right)} \]
Fick’s Principle

\[ C_aO_2 \text{ blood flow } C_vO_2 \]

\[ \text{blood flow}_{\text{system}} = \frac{\text{oxygen consumption}}{\text{oxygen content change}} \]

\[ \text{oxygen consumption} = \text{blood flow}_{\text{system}} \times \text{oxygen content change} \]
Oxygen consumption ($\dot{\text{VO}}_2$)

\[
\begin{align*}
\dot{\text{VO}}_2 & = \text{blood flow}_{\text{system}} \cdot \text{oxygen content change} \\
& = \text{cardiac output (Q}_s) \cdot 0.0136 \cdot \text{Hb} \cdot (S_{a}\text{O}_2 - S_{v}\text{O}_2) \\
& = \text{heart rate} \cdot \text{stroke volume} \cdot 0.0136 \cdot \text{Hb} \cdot (S_{a}\text{O}_2 - S_{v}\text{O}_2) \\
& = \text{HR} \cdot \text{EF} \cdot \text{LVV}_{\text{ed}} \cdot 0.0136 \cdot \text{Hb} \cdot (S_{a}\text{O}_2 - S_{v}\text{O}_2)
\end{align*}
\]
Oxygen uptake ($\dot{V}O_2$)

\[ \dot{V}O_2 = \text{blood flow}_{\text{system}} \cdot \text{oxygen content change} \]

\[ = \text{cardiac output (Q}_s) \cdot 0.0136 \cdot \text{Hb} \cdot (S_aO_2 - S_vO_2) \]

\[ = \text{heart rate} \cdot \text{stroke volume} \cdot 0.0136 \cdot \text{Hb} \cdot (S_aO_2 - S_vO_2) \]

\[ = \text{HR} \cdot \text{EF} \cdot \text{LVV}_{\text{ed}} \cdot 0.0136 \cdot \text{Hb} \cdot (S_aO_2 - S_vO_2) \]

chronotropy
systolic function
diastolic function
$O_2$ transport capacity
$O_2$ extraction
Oxygen Cost for Work

Oxygen uptake (ml/min) vs. Work (Watts)

17 healthy subjects

slope = 9.9 ± 0.7 ml/min/watt

Wassermann, 4. Aufl. 2005
Oxygen uptake
Heart rate – $\dot{\text{VO}_2}$
Oxygen Pulse

= oxygen uptake / heart rate
  ( = „oxygen transport / heart beat“ )

= \( \text{HF} \cdot \text{EF} \cdot \text{LVV}_{ed} \cdot 0.0136 \cdot \text{Hb} \cdot (S_aO_2 - S_vO_2) \)

= stroke volume \cdot oxygen content change
Oxygen Pulse
Cardiac Work

Energy = P \cdot V

Work = dP \cdot dV

Ventricular Volume (ml)
Energy = P · V

Work = dP · dV
Cardiac Power

\[ \dot{W} = \text{work} / \text{time} \quad (= \dot{W}) \]
\[ = \text{heart rate} \cdot \text{cardiac work} \]
\[ \approx \text{heart rate} \cdot \text{stroke volume} \cdot \text{SBP} \]

\[ \dot{V}O_2 = \text{cardiac volume} \cdot \text{oxygen content change} \]
Circulatory Power

= cardiac output \cdot oxygen content change \cdot SBP
  (= oxygen uptake \cdot SBP)
  (= cardiac power \cdot oxygen content change)

= HF \cdot EF \cdot LVV_{ed} \cdot 0.0136 \cdot Hb \cdot (S_aO_2 - S_vO_2) \cdot RR
Circulatory Power

Exercise haemodynamic variables rather than ventilatory efficiency indexes contribute to risk assessment in chronic heart failure patients treated with carvedilol

peakSBP, Circulatory Power and oscillatory breathing are the best predictors
CPET Cube

- Circulatory work
- Cardiac work
- Stroke volume × BP
- Cardiac output × HR
- Circulatory work
- Cardiac output × BP
- Circulatory power
- Cardiac power
- O₂ uptake
- O₂ pulse
- O₂ transport capacity
- O₂ extraction

Equation:

\[ \text{circulatory work} = \text{stroke volume} \times \text{HR} \times \text{O}_2 \text{ transport capacity} \times \text{O}_2 \text{ extraction} \]

\[ \text{cardiac work} = \text{stroke volume} \times \text{HR} \times \text{O}_2 \text{ transport capacity} \times \text{O}_2 \text{ extraction} \]

\[ \text{cardiac output} = \text{stroke volume} \times \text{HR} \times \text{BP} \]

\[ \text{circulatory power} = \text{cardiac power} \times \text{BP} \]
Limitations of the Model

• Mitral / aortic valve regurgitation: stroke volume ≠ effective aortic stroke volume
• Cardiac work with only SBP (without volume pressure loops) ?
• Cardiac work without right ventricular work ?
• In congenital heart defects with shunts there is not a single cardiac output: $\dot{Q}_P$, $\dot{Q}_S$
• What is the physical background of „circulatory power / work“ (gas flow · BP) ?
Limitations of the Model

- Mitral / aortic valve regurgitation: stroke volume ≠ effective aortic stroke volume
- Cardiac work with only SBP (without volume pressure loops) ?
- Cardiac work without right ventricular work ?
- In congenital heart defects with shunts there is not a single cardiac output: $Q_B, Q_S$
- Without the right ventricle, only oxygen pulse and oxygen uptake are reliable for all patients