Pléthysmographie opto-électronique: analyse cinématique des mouvements thoraciques chez le sujet sain et le patient.

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Pléthysmographie opto-électronique?

• C’est quoi POE (Anglais: OEP)?
• Exemples d’application
  – Sujets sains
  – Clinique
• Perspectives
Comment mesurer le volume pulmonaire absolu en continu ?

- Techniques de dilution / washout, plethysmographie → ‘one-shot’
- CRF + intégration du flux à la bouche: problème de la dérive
- CRF + magnétomètres ou respitrace: manque de précision
- CRF + OEP (Opto-Electronic Plethysmography)

Opto-Electronic Plethysmography (OEP)

Camera → Analyse de la motion

Position des marqueurs → Modèle géométrique

Calcul du volume

Changements dynamiques du volume thoracique (Vcw)

Aliverti et al. Am J Respir Crit Care Med, 2000
account for these differences during quiet breathing which were often only 10% of the tidal volume signal. If this had been the case, the phase of \( V_{bs} \) would always bear the same relationship to the phases of \( D V_b \) and \( D V_{tr} \). But this was not what was observed. When diaphragmatic breathing was changed to rib cage breathing the phase of \( V_{bs} \) changed according to the phase of \( P_{ab} \), not \( V_b \) and \( V_{tr} \) (fig 1-A). Similarly when abdominal muscle contraction occurred either voluntarily or during quiet breathing, the phase of \( V_{bs} \) became biphasic, in phase with the biphasic increases in \( P_{ab} \) during both inspiration and expiration. Therefore the blood shifts we measured during quiet breathing could not have resulted from minor calibration differences between the OEP and WBP signals. Furthermore, when breathing took place with only minimal fluctuations in \( P_{ab} \) we found, as predicted, that the blood shifts were very small and the WBP and OEP tracings were essentially identical. Figure 1-A shows this to be the case. The small fluctuations ranging between \(+20\) and \(+250\) ml approximately \(0^\circ\) out of phase with \( P_{pl} \) swings are easily explained by small fluctuations in intrathoracic volume resulting from the changes in pleural pressure.
Period B
(2 min)
constant set
(15 min)

Period A
(2 min)
constant set
(15 min)

Period C
(2 min)

Dellacà et al.,
Crit Care Med, 2001

Figures 4. Linear regression (left panel) and Bland-Altman (right panel) analysis between 300 ml
and constant tidal volume ventilation strategies by the different techniques and strategies used
in the present study. The regression parameters were by EELV and the remaining set
and volume ventilation strategies by OEP. The horizontal line represents a level of performance
and tidal Reference line, while the dotted line between periods A and period E.

Aliverti et al.,
JAP, 2007

300 ml
Exemple 1: mesure des changements dynamiques des réserves d’O₂ pulmonaire

- La mesure de l’échange gazeux alvéolaire est fondamentale pour l’étude des mécanismes de couplage entre métabolisme aérobie, transport cardiovasculaire et ventilation.

- La majorité des appareils commerciaux de calorimétrie indirecte mesurent la V’O₂ respiration par respiration (BbB).

- Quels sont les effets de changements dynamiques de volumes pulmonaires sur les valeurs BbB?

\[
VO_{2,mi} = \int F_{I02} \dot{V} \_i \, dt - \int F_{EO2} \dot{V} \_E \, dt
\]
Sources d’erreur en respiration par respiration (BbB)

- Temps de délai entre échantillonnage et mesure de composition de gaz expiré
- Temps de réponse des analyseurs
- Humidité
- Dérive d’intégration
- Changements dynamiques des réserves de gaz pulmonaires:
  - Changements du volume pulmonaire en fin d’expiration (EELV)
  - Changements des concentrations de gaz du début à la fin d’une respiration

Volume d’oxygène échangé à la bouche

\[ V_{O_2,mi} = \int F_{I02} \dot{V}_I \, dt - \int F_{EO2} \dot{V}_E \, dt \]
Volume d’oxygène dans les poumons au début de l’inspiration
Volume d’oxygène dans les poumons à la fin de l’expiration

\[ F_{O_2} \]

\[ 0 \] \[ 1 \] \[ 2 \] \[ 3 \] \[ 4 \] \[ 5 \]

\[ 0.00 \] \[ 0.04 \] \[ 0.08 \] \[ 0.12 \] \[ 0.16 \] \[ 0.20 \]

Volum d’oxygène dans les poumons à la fin de l’expiration

\[ V_{F_{O_2}} - 1 \cdot \frac{\Delta F_{A_i, O_2}}{F_{A_i, O_2}} \pm \frac{\Delta V_{A_i}}{\Delta V_{A_{O_2}}} \]

Variation de la fraction à volume constant

Variation du volume à fraction constante
Volume d’oxygène échangé à la bouche (Vo₂,m)

Volume d’oxygène pris par le sang (Vo₂,A)
\[ VO_{2,Ai} = VO_{2,mi} - \Delta VO_{2,si} \]

- Analyseurs de gaz commerciaux ne prennent pas en compte ce problème

- Des approches de calcul différentes non pas resolu le problème
  
  (Auchincloss, 1966; Swanson, 1980; Wessel, 1983; Grønlund, 1984; Busso, 1997)

- “... the approach of measuring the subject’s FRC and then calculating the actual alveolar volume at the end of each expiration ... may well become in the future the ideal method for assessing breath-by-breath alveolar gas transfer”

  (Capelli et al, Eur J Physiol, 2001)
Validation: méthodes

Sujets
7 hommes (26-47 yrs)

Protocole
- CRF par rinçage d’azote
- Test d’effort incremental sur cycloergomètre
  (repos, zero watt, ensuite +20 watt / 5 min jusqu’à 120 watt)
- à chaque niveau collecte de gaz exprès pendant 2 minutes dans sac de Douglas

Mesures
- O₂ (paramagnétique, Servomex)
- Débit (pneumotachograph)
- Vcw par OEP
- À chaque palier, F₄O₂ Douglas mesuré par le même analyseur de gaz que FO₂ à la bouche

(Aliverti et al. 2004)

Validation

Analyses
VO₂ avec Douglas (‘gold standard’)
VO₂,BbB = V₄,F₄O₂ – V₆,F₆O₂

BbB VO₂ (VO₂,BbB)
  Alignement avecVL
  Correction la dérive de l’intégration
  Synchronisation des signaux O₂ et VL
  Correction pour changements de réserves d’oxygène pulmonaires

Comparaison entre VO₂,BbB and VO₂,old

(Aliverti et al. 2004)
Validation

(Aliverti et al. 2004)
Implications

(Aliverti et al. 2004)
Implications

(Aliverti et al. 2004)

Quantification BbB des variations de réserves d’oxygène pulmonaires

• Comparaison de V’O$_2$$_{m}$ (différence entre O$_2$ inspiré et expiré) et V’O$_2$$_{A}$ (avec correction pour les changements des réserves pulmonaires d’oxygène)

• Hypothèses:
  - V’O$_2$$_{A}$ contient moins de ‘bruit’ BbB
  - V’O$_2$$_{A}$ augmente plus vite au début de l’effort
Résultats

Table 2. Mean and standard deviations of BbB VO2 during the last minute of the 6-minutes-period, measured at the mouth and at the alveolar level. Values are mean (std), n=7.

<table>
<thead>
<tr>
<th>Variable breathing</th>
<th>mean V'O2,M (l/min)</th>
<th>mean V'O2,A (l/min)</th>
<th>std V'O2,M (l/min) * #</th>
<th>std V'O2,A (l/min) * #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>0.227 (0.056)</td>
<td>0.246 (0.049)</td>
<td>0.451 (0.185)</td>
<td>0.264 (0.192)</td>
</tr>
<tr>
<td>60 W</td>
<td>0.759 (0.061)</td>
<td>0.750 (0.065)</td>
<td>0.369 (0.165)</td>
<td>0.223 (0.164)</td>
</tr>
<tr>
<td>90 W</td>
<td>0.991 (0.115)</td>
<td>0.972 (0.091)</td>
<td>0.503 (0.301)</td>
<td>0.265 (0.145)</td>
</tr>
<tr>
<td>120 W</td>
<td>1.248 (0.105)</td>
<td>1.248 (0.103)</td>
<td>0.472 (0.276)</td>
<td>0.238 (0.088)</td>
</tr>
</tbody>
</table>

† Effect of intensity (p < 0.001). This effect was significant between all intensities (p < 0.001).
* Difference between V'O2,M and V'O2,A (p < 0.005)
# Difference between variable breathing and rest (p < 0.001)
The main purpose of this study was to directly measure variation in pulmonary oxygen stores during rest, transient to and steady state exercise of 60, 90 and 120 W compared to \( \dot{V}_{\text{AO2}} \).


during rest, transient to and steady state exercise of 60, 90 and 120 W compared to \( \dot{V}_{\text{AO2}} \).

Representative graph for oxygen uptake as measured at the mouth (\( \dot{V}_{\text{MO2}} \)) and corrected for alveolar gas stores (\( \dot{V}_{\text{AO2}} \)). Note the significant higher variation in \( \dot{V}_{\text{MO2}} \)

\[
\frac{\Delta \dot{V}_{\text{MO2}}}{\dot{V}_{\text{MO2}}} = \frac{\dot{V}_{\text{MO2}}(\text{int} - 1) - \dot{V}_{\text{MO2}}(\text{int})}{\dot{V}_{\text{MO2}}(\text{int})} \times 100
\]

\[
\frac{\Delta \dot{V}_{\text{AO2}}}{\dot{V}_{\text{AO2}}} = \frac{\dot{V}_{\text{AO2}}(\text{int} - 1) - \dot{V}_{\text{AO2}}(\text{int})}{\dot{V}_{\text{AO2}}(\text{int})} \times 100
\]

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\frac{\Delta \dot{V}_{\text{AO2}}}{\dot{V}_{\text{AO2}}} = \frac{\dot{V}_{\text{AO2}}(\text{int} - 1) - \dot{V}_{\text{AO2}}(\text{int})}{\dot{V}_{\text{AO2}}(\text{int})} \times 100
\]
Fig. 5. Mean values and standard deviation for the change in end-expiratory lung volume (see Section 2 and Fig. 5). These factors explain variability of oxygen uptake is reduced substantially (∼55% of the variance between the difference between ˙VMO2 and ˙VAO2 .

When oxygen uptake is measured as the difference between ˙VMO2 and ˙VAO2 , suggesting that other factors must play a role too. It is possible that expiratory FO2 is influenced by respiratory frequency and from exercise and that this affects oxygen uptake at the mouth (Fig. 6). Differences between ˙VMO2 and ˙VAO2 are caused by volume differences and changes in oxygen fraction at constant oxygen fraction and changes in oxygen fraction at constant oxygen fraction and changes in oxygen fraction at constant oxygen fraction (Lamarra et al., 1987; Ozyener et al., 2001). Instead of assigning pulmonary oxygen stores change rapidly during transients to estimate BbB changes of alveolar gas stores, the time constant demonstrates that, by applying the algorithm of Grønlund (1984) which assumes a given absolute value of VL(1) amplifies the weight of alveolar gas store to FRC + 0.5 L. This was essentially due the fact that the absolute lung volume during the protocol (on and off-transients at 60, 90 and 120 W) for all participants. Letters A–E represent the mean values for each minute, where B is split up in four periods of 15 s (see Section 2.5 for more details). Significant higher ˙VAO2 compared to ˙VMO2 introduces large errors when interpreting it as ˙VAO2 .

Aliverti et al. (1997) and Henke et al. (1988) showed that this is caused by changes in pulmonary blood flow or changes in capillary membrane is significantly higher than as measured at the mouth (Fig. 5C). This was mainly due to a reduction of pulmonary oxygen stores present in the lung at the end of each breath (Suskind et al., 1950; Beaver et al., 1981) rapidly decrease during transients to increased pulmonary blood flow or changes in cardio-dynamic phase (Lamarra et al., 1987; Ozyener et al., 2001). Instead of assigning the phase II was shorter than that calculated on the basis of the classical algorithms of BbB oxygen uptake measurement. OEP adequately overcomes this problem and, after correction of pulmonary gas exchange at the onset of exercise, because VL(1) intrapulmonary gas mixing, independently from changes in VLET.

Respiration variable (repos)

▽: \( \dot{V'O}_2,m \)

●: \( \dot{VO}_2,A \)

Fig. 1. BbB \( \dot{V'O}_2 \) responses of a typical subject at the onset of the exercise performed at 60, 90 and 120 W. Blue lines: BbB \( \dot{V'O}_2 \) estimated by applying the algorithm of Grønlund (GR); red lines: alveolar \( \dot{V'O}_2 \) obtained using opto-electronic plethysmography (OEP); black lines: difference between GR and OEP BbB \( \dot{V'O}_2 \).

Finally, normalised amplitudes at each workload were calculated by dividing the amplitude of the first or second single component by their sum:

\[
\begin{align*}
A_{1N} &= \frac{A_1}{A_1 + A_2} \\
A_{2N} &= \frac{A_2}{A_1 + A_2}
\end{align*}
\]

2.6. Statistics
The data are reported as mean ± SD. The between method and load differences were evaluated by using a two-way analysis of variance (Sigmastat, 3.11, Systat software, USA). Normality of the data distributions was evaluated by means of a Shapiro-Wilk test. A post hoc Holm-Sidak test was used to identify significant differences between paired sets of data obtained by using the different algorithms.

P < 0.05 was used as minimum significance level.

3. Results
Fig. 1 shows the BbB \( \dot{V'O}_2 \) response of a typical subject at the onset of the exercise performed at 60, 90 and 120 W. The blue lines represent GR BbB \( \dot{V'O}_2 \), the red ones refer to OEP measured alveolar \( \dot{V'O}_2 \) and the black ones to the difference between GR and OEP.

One can see that during the early transient GR values lag with regard to OEP values because of a reduction in alveolar oxygen stores. OEP values were characterised by an higher level of BbB variability reflecting sometimes large differences between inspired and expired volume within one single breath.

The MRTs of the \( \dot{V'O}_2 \) responses were not affected by the imposed workload, regardless of the algorithm used for calculating BbB \( \dot{V'O}_2 \).

However, MRT calculated by analysing MO BbB \( \dot{V'O}_2 \) values turned out to be smaller than those obtained by using GR at 120 W. Finally, MRT obtained by utilising GR was also significantly larger than that obtained by analysing OEP BbB data at 90 W (Fig. 2, Table 1).

Fig. 2. Mean response time (MRT) values plus standard deviations of \( \dot{V'O}_2 \) kinetics at the three indicated workloads. They were calculated on the basis of the normalised amplitudes, time delays and time constants estimated by fitting the BbB \( \dot{V'O}_2 \) data calculated at the mouth, with OEP and Grønlund's algorithm. The short segments reported above the histograms connect the MRT values that turned out to be significantly different. P-values are also indicated.

4. Discussion
In this study we described \( \dot{V'O}_2 \) kinetics at the onset of constant-load, moderate intensity cycling exercise, fitting BbB \( \dot{V'O}_2 \) data obtained with three different algorithms. First, we calculated \( \dot{V'O}_2 \) at the mouth (MO) over each single breath. Second, we estimated BbB lung volume and O2 alveolar stores variations by using the algorithm of Grønlund (GR) so that O2 alveolar transfer could be calculated. Finally, by using OEP, the absolute changes of lung gas volume – and the BbB changes in lung O2 stores and O2 alveolar transfer deriving there from – were directly measured BbB.

The results show that \( \dot{V'O}_2 \) responses described by fitting GR BbB \( \dot{V'O}_2 \) uptake were significantly slower than those obtained by fitting MO or OEP BbB data. Moreover, the normalised amplitude of the so-called cardiodynamic phase, the increase in \( \dot{V'O}_2 \) in the first 10–20 s after onset of exercise, turned out to be significantly larger when \( \dot{V'O}_2 \) responses were assessed by using OEP.

In the following paragraphs we discuss some of the technical issues of the calculation of BbB \( \dot{V'O}_2 \) that may explain the observed differences in the results obtained with the three methods. Finally,
Fig. 1. BbB $\dot{V}O_2$ responses of a typical subject at the onset of the exercise performed at 60, 90 and 120 W. Blue lines: BbB $\dot{V}O_2$ estimated by applying the algorithm of Grønlund (GR); red lines: alveolar $\dot{V}O_2$ obtained using opto-electronic plethysmography (OEP); black lines: difference between GR and OEP BbB $\dot{V}O_2$.

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\[
A_1^N = \frac{A_1}{A_1 + A_2} \quad (5a)
\]

\[
A_2^N = \frac{A_2}{A_2 + A_2} \quad (5b)
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In the following paragraphs we discuss some of the technical issues of the calculation of BbB $\dot{V}O_2$ that may explain the observed differences in the results obtained with the three methods. Finally,

Conclusions

- Réponses 'on' (et 'off'): meilleure compréhension de l’influence des réserves d’oxygène pulmonaires
  - Pas d’exclusion de valeurs extrêmes
  - Pas besoin de filtrer
- OEP devient le ‘gold standard’ pour la mesure BbB des échanges gazeux
- Doit être utilisée quand des changements des réserves d’oxygène pulmonaires sont attendus (par exemple pendant des transitions)
Exemple 2

- La double pléthysmographie
- Comment distinguer les changements de volume thoracique dus au:
  - gaz (volumes déplacés, effets de compression et dilatation)
  - sang (entre compartiments thoraciques (pulmonaire, abdominale) et membres)?
La pompe abdominale

• Au repos 50–75 ml de sang / cycle respiratoire est propulsé vers les extrémités (4–6% du volume total), pour un débit de 750–1500 ml/min
• Une action coordonnée entre diaphragme et muscle expiratoires peut développer un débit de 6 L/min
Exemple 3

- Facteurs limitant l’effort en BPCO: hyperinflation vs. non-hyperinflation
- Effets d’inhalation de Héliox pendant un test d’effort à 75% max jusqu’à l’épuisement

Louvaris et al., 2012
Conclusions

- Héliox améliore la performance de façon différente entre hyperinflation et non-hyperinflation
- Mais toute stratégie envers une amélioration de l’interaction cardio-pulmonaire est potentiellement utile peu importe le type (hyperinflation ou non-hyperinflation)

OEP

- Devient ‘main stream’
- Est utile pour toute étude de dynamique nécessitant une mesure des volumes absolus
- Un système est prévu à l’Unil
Perspectives

• Etudes sur l’humain sain:
  – Coordination entre respiration et foulée de course
  – Entrainement des muscles expiratoires et débit cardiaque pendant l’effort

• Chez le patient
  – Effets de la réhabilitation respiratoire sur l’interaction entre système pulmonaire et cardiovasculaire