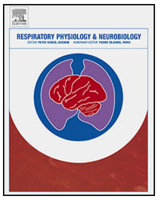
Respiratory Physiology & Neurobiology 205 (2015) 77–83

Contents lists available at ScienceDirect

Respiratory Physiology & Neurobiology

journal homepage: www.elsevier.com/locate/resphysiol



Electrical activity of the diaphragm during progressive cycling exercise in endurance-trained men

Mathias Krogh Poulsen[a,*], Lars Pilegaard Thomsen[a], Nicolai Lees Mifsud[a], Niels-Peter Brøchner Nielsen[a], René Melvad Jørgensen[a], Søren Kjærgaard[b], Dan Stieper Karbing[a]

[a] *Respiratory and Critical Care Group, Department of Health Science and Technology, Aalborg University, Fredrik Bajers vej 7, E4, Aalborg East, 9220 Aalborg, Denmark*
[b] *Department of Anesthesiology, Aalborg University Hospital, 9000 Aalborg, Denmark*

ARTICLE INFO

Article history:
Accepted 20 October 2014
Available online 24 October 2014

Keywords:
Diaphragm
Progressive
Exercise
Respiratory
Drive
Reliability

ABSTRACT

The study aimed to investigate diaphragm respiratory drive modulation through electrical activity of the diaphragm (EADi) during progressive cycling in endurance-trained men ($N = 7$) and to test day-to-day measurement reliability. Normalized EADi increased at exercise intensities from 40% workload (WL) to 70% and 85%WL but plateaued from 70% to 85% ($p < 0.05$). $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, increased at all exercise intensities, where Vt and BF increased from 40% to 55% WL and from 70% to 85% and RER increased at 70% and 85% ($p < 0.05$). Bland–Altman plots of normalized EADi showed bias of 0.9% and −6.4% and limits of agreement of ±36.0% and ±30.4% for absolute measurements and relative changes from 40% WL, respectively. Within-day variability appeared constant indicating that measurements within a trial are reliable. Results suggest that diaphragm respiratory drive increases at moderate exercise intensities, but plateaus at high intensities where other respiratory muscles might contribute significantly to the breathing effort, perhaps to "protect" against diaphragm fatigue.

1. Introduction

The majority of previous studies of respiratory drive modulation have applied measurements of either voluntary inspiratory mouth pressure, or pressure evoked through magnetic stimulation of the phrenic nerve (Clanton and Diaz, 1995; Verin et al., 2004). These measurements were performed pre and post fatiguing exercise (Babcock et al., 1995; Verin et al., 2004) and may therefore fail to accurately estimate the diaphragm respiratory drive modulation during exercise.

Respiratory drive modulation of the diaphragm can also be estimated through measurement of electrical activity of the diaphragm (EADi) via an esophageal catheter. This method allows measuring directly at the diaphragm during actual exercise and thereby provide accurate assessment of the respiratory drive modulation during voluntary breathing (Qin et al., 2010). EADi has been used to measure the work of the diaphragm at different lung capacities (Beck et al., 1998), and fatigability during CO_2 rebreathing efforts (Luo et al., 2001) or in whole body exercise during constant load cycling in elderly normal and COPD patients (Qin et al., 2010). So far, only Zhang et al. (2013) have measured EADi during progressive exercise to exhaustion. They recently showed that EADi measured via an esophageal catheter increased progressively during incremental cycling, thus indicating, in contrast to general belief, that respiratory drive modulation of the diaphragm was not reduced at any exercise intensity during progressive exercise to exhaustion (Zhang et al., 2013). However, in the study by Zhang et al. (2013), the subjects were untrained. This is important as, during exercise, the respiratory system is not a limitation for untrained individuals as it can be with endurance-trained subjects (Romer and Polkey, 2008). This might explain why the electrical activity of the diaphragm did not plateau as expected in the study by Zhang et al. (2013). Further, Walker et al. (2011) showed in endurance-trained subjects that diaphragm twitch pressure decreased during progressive high intensity exercise, also indicating a diaphragm respiratory drive modulation during exercise.

Previous studies of EADi have showed that during CO_2 rebreathing, EADi was not influenced by esophageal peristalsis, catheter placement and movement or lung-volume, (Beck et al., 1998; Luo et al., 2001). However the reliability of EADi measurements during exercise has not been investigated.

---

* Corresponding author. Tel.: +45 2829 7625.
E-mail address: mkpo@hst.aau.dk (M.K. Poulsen).

http://dx.doi.org/10.1016/j.resp.2014.10.012
1569-9048/

Therefore, the aims of this study were to quantify the respiratory drive of the diaphragm in endurance-trained men during a progressive cycling trial and further to evaluate the reliability of these measurements. It was hypothesized, that respiratory drive to the diaphragm would increase during submaximal intensities and reach a plateau during high intensity. The reliability of EADi measurements were investigated within subjects between two identical trials of progressive cycling.

2. Methods

2.1. Participants

Seven endurance trained male triathletes or runners, with no smoking history, participated in the study: mean ± SD age; 28.3 ± 4.7 [yrs]; height: 184.2 ± 10.7 [cm]; weight: 80 ± 9.4 [kg]; $\dot{V}O_{2\,max}$: 59 ± 4 [ml kg^{-1} min^{-1}]. The study was approved by the local ethics committee and all subjects gave their written informed consent.

2.2. Cycling trials

2.2.1. $\dot{V}O_{2\,max}$ test

First, a maximal oxygen consumption ($\dot{V}O_{2\,max}$) test was performed on a cycling ergometer (Monark ergomedic Peak Bike 894 E, Vansbro, Sweden) to determine the subject's $\dot{V}O_{2\,max}$ and to estimate workload stages for the following incremental EADi trials. Following warm-up, two 4 min stages at 160 and 240 watts were performed, where-after, 50 watt increments each 30 s were applied until either; respiratory exchange ratio (RER) was >1.10, the heart rate was near age-estimated maximum or oxygen consumption ($\dot{V}O_2$) plateaued. Excluding warm-up, test time was maximally 12 min.

2.2.2. EADi trial 1 and 2

To investigate the electrical activity of the diaphragm, two incremental cycling trials (EADi trial 1 and 2) were performed. EADi trial 1 was performed after at least 48 h of recovery from the $\dot{V}O_{2\,max}$ test, and EADi trial 2 was performed 6 to 20 days following trial 1.

Both EADi trials were initiated by familiarizing the subjects to maximum inspiratory capacity maneuvers (icmax) from functional residual capacity. After familiarizing to the icmax maneuver, the subjects performed 2 sessions (separated by a 3 min break) of 5 icmax with 10 s interspace. During the icmax, the subject was instructed to sit in an upright position on the ergometer and inspire as fast and hard as possible to maximum inspiratory capacity and then expire slowly (Sinderby et al., 1998). Verbal encouragement was given to all subjects to ensure maximal effort.

2 min after the icmax, 4 min unloaded cycling warm-up was performed. The trial continued with 4 stages of 4 min duration where the loads were 40, 55, 70 and 85% of maximal workload (WL). WL was calculated from the previously described $\dot{V}O_{2\,max}$ trial by linear regression of the watt/ $\dot{V}O_2$ measurements from the two submaximal steady states.

During the last 30 s of each WL stage, the subjects sat upright while still pedaling where respiration, gas exchange and EADi data were acquired. This body position was applied, since it was also used when positioning the catheter prior to testing and during the icmax. Pedaling frequency was kept constant at 80 revolutions per minute with a metronome (Korg MA-30, Korg Inc. Japan) and with visual feedback from the ergometer-display.

2.3. Equipment and measurements

Respiration and gas exchange measurements ($\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$), minute volume ($\dot{V}E$), RER, tidal volume (Vt) and breathing frequency (BF)) were obtained with a respiratory gas analyzer (Oxycon Pro, Jaeger, Cardinal Health, Hoechberg, Germany). Measurements were reported as a 5 s average of breath by breath sampling with LabManager (v. 5.21, Carefusion, Höchberg, Germany). This configuration for respiration and gas measurements was applied in all exercise tests throughout the study.

Prior to EADi trial 1 and 2, the subjects were fitted with an esophageal multi-cited EMG-catheter (NAVA, Maquet, Solna, Sweden) designed for mechanically ventilated patients. The catheter was inserted following the guidelines outlined by the manufacturer. The catheter was inserted through the nose and swallowed by the subjects to a pre-calculated depth as outlined by the manufacturer. The initial depth was the same for each trial within subjects and was the distance from nasal bridge to earlobe to xiphoid process multiplied by 0.9 and added to 18 (in cm). Then the catheter was moved up to a few centimeters up or down to secure maximal signal strength at the central electrode pair of the catheter as was visualized in the Edi catheter positioning mode on the ventilator. The EADi signal was acquired and processed according to the American Thoracic Society recommendations (Aldrich et al., 2002). The catheter was 125 cm long, had a diameter of 2.7 mm and had 10 electrodes with an inter-electrode distance of 16 mm. The catheter was connected to a ventilator (Servo-I, Maquet, Solna, Sweden) with software used to verify catheter-placement and for storage of EADi data. The NAVA system performed amplification and on-line digital processing of 16 ms segments of EADi. This processing includes selection of the electrode pair closest to the crural diaphragm (Sinderby et al., 1999); filters and algorithms for maximizing signal-to-noise ratio (Sinderby et al., 1997); avoidance of interference due to changes in muscle length, lung volume and chest wall configuration by taking diaphragm position along the electrode array into account (Beck et al., 1997 and 1998; Sinderby et al., 1997) and replacing signal portions containing residual disturbances such as cardiac electric activity with values of previous segments (Sinderby et al., 1999, 2007). The output EADi is a root-mean-square of the processed diaphragm EMG signal (Sinderby et al., 2001). Subsequently, the catheter was fixed at the nostrils and a soft face-mask (Hans Rudolph, Inc., USA) held the catheter steady while being airtight to avoid gas leakage. The processed EADi data were extracted from the ventilator in 100 Hz resolution to a personal computer using software provided by the manufacturer (Servo Tracker v4.0, Maquet, Solna, Sweden). An example of the processed EADi signal recorded from both trials is shown in Fig. 1.

2.4. Data processing and statistical analysis

All outcome measures were analyzed from the last 25 s of each exercise intensity. MATLAB (Version R2013b, MathWorks) was used for all data processing, and SPSS (Version 22, IBM) was used for all statistical analysis.

Peak EADi from each breath during the period of interest was selected for further analysis. Each peak EADi value was normalized to percentage of the highest EADi peak measured during icmax or the highest EADi peak obtained throughout the entire trial. Mean normalized EADi ($\text{EADi}_{\%\text{icmax}}$) was calculated within each subject for every WL within each trial. To test for significant changes between the WL, repeated measures ANOVA with Bonferroni adjusted post hoc tests were applied on all parameters with *p*-values less than 0.05 considered statistically significant. Descriptive statistics are reported as mean ± SD across the 7 subjects.

Between trial and within subject reliability of EADi results were evaluated by comparing EADi measured during the two incremental EADi trials using Bland–Altman plots with ANOVA repeated