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Effect of non-invasive ventilation on the measurement of ventilatory and metabolic variables

C.J. Dennis[a,*], C. Menadue[b], A.R. Harmer[a], D.J Barnes[b,c], J.A. Alison[a,d]

[a] Faculty of Health Sciences, The University of Sydney, Sydney, Australia
[b] Department of Respiratory & Sleep Medicine, Royal Prince Alfred Hospital, Sydney, Australia
[c] Faculty of Medicine, The University of Sydney, Sydney, Australia
[d] Department of Physiotherapy, Royal Prince Alfred Hospital, Sydney, Australia

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ABSTRACT

The effect of non-invasive ventilation (NIV) on the accuracy of measurements of ventilation, oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) was examined using a simulator. Known gas volumes of oxygen and carbon dioxide were delivered to a metabolic system that measured tidal volume, respiratory rate, $\dot{V}O_2$ and $\dot{V}CO_2$, both with and without NIV. Bland-Altman analyses were used to compare between conditions. NIV at pressure support (PS) 20 cm H_2O compared to without NIV showed: V_T, mean difference (MD) 0 mL (limits of agreement (LOA) −21 to 21) mL; $\dot{V}O_2$ MD −413 (LOA −810 to 16) mL/min; and $\dot{V}CO_2$ MD 32 (LOA −32 to 97) mL/min. For $\dot{V}O_2$ measurements during NIV, a correction was applied to account for increased air density due to PS. After correction, $\dot{V}O_2$ measurement accuracy improved; MD −46 (LOA −108 to 17) mL/min. Tidal volume and metabolic variables can be measured with acceptable accuracy during NIV, providing $\dot{V}O_2$ is corrected for altered gas density.

1. Introduction

Non-invasive ventilation (NIV) is a therapy in which positive pressure is used to provide ventilatory support through the upper airway via a mask or similar device (Nava and Hill, 2009). NIV during exercise has been shown to improve exercise capacity among people with chronic obstructive pulmonary disease (COPD) (van't Hul et al., 2006, 2002) by reducing dyspnoea and unloading the respiratory muscles (Kyroussis et al., 2000; Maltais et al., 1995). When respiratory muscle unloading is successful it appears to be associated with a reduction in oxygen consumption ($\dot{V}O_2$) of the respiratory muscles at high work rates in healthy people (Harms et al., 1998). Previous research studies have used tailor-made (Aaron et al., 1992) and commercially available (Borghi-Silva et al., 2008; Moga et al., 2014) equipment to measure ventilatory and metabolic variables when NIV is used during exercise, however, the accuracy of commercially available systems to measure these variables during NIV is unknown.

A commercially available metabolic system, the K4b2 (Cosmed, S.r.l., Rome, Italy) measures fraction of inspired oxygen (F_IO_2), fraction of expired oxygen (F_EO_2), fraction of expired carbon dioxide (F_ECO_2), tidal volume (V_T) and respiratory rate (fR) to calculate $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$) and minute ventilation ($\dot{V}_E$). Measured variables are logged and displayed on a breath-by-breath basis for analysis (Stickland et al., 2012; Wasserman, 1997). For the measurement of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$, the K4b2 has been validated against the Douglas bag method at work rates from rest to 200 W (Duffield et al., 2004; McLaughlin et al., 2001). However, the addition of NIV may affect the measurement accuracy of ventilatory and metabolic variables. For example, Borghi-Silva et al. (2008) reported that $\dot{V}CO_2$ measurements were significantly lower with proportional assist ventilation than without (up to 300 mL/min difference), and consequently were not analysed.

Since the application of NIV in humans alters ventilatory and metabolic variables (Harms et al., 1998), it is not possible to systematically assess the effects of NIV on measurement accuracy compared to breathing without NIV in vivo. To enable the comparison between these different conditions, repeatable production of known variables using mechanical simulation is required. The aim of the present study was to examine the effect of measurements with NIV compared to without NIV on the measurement accuracy of V_T, fR, $\dot{V}O_2$ and $\dot{V}CO_2$ using mechanical simulation of ventilatory and metabolic variables.

* Corresponding author at: Discipline of Physiotherapy Faculty of Health Sciences, University of Sydney, 75 East Street, Lidcombe, NSW 2141, Australia.
E-mail address: cden2754@uni.sydney.edu.au (C.J. Dennis).

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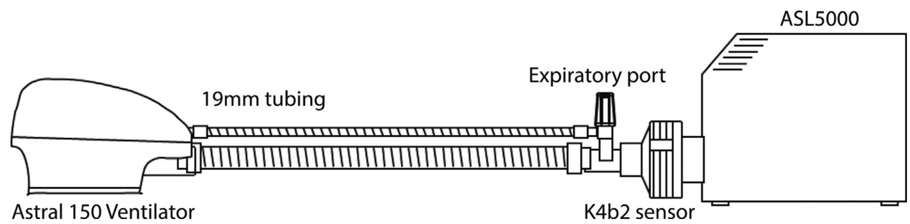

Fig. 1. A representation of the ASL5000 connected to the Astral 150 ventilator. The system consists of (from the left) the Astral 150, 19 mm tubing and pressure lines, expiratory valve and pressure connection point, K4b2 turbine and gas sampling point, ASL5000 piston simulator.

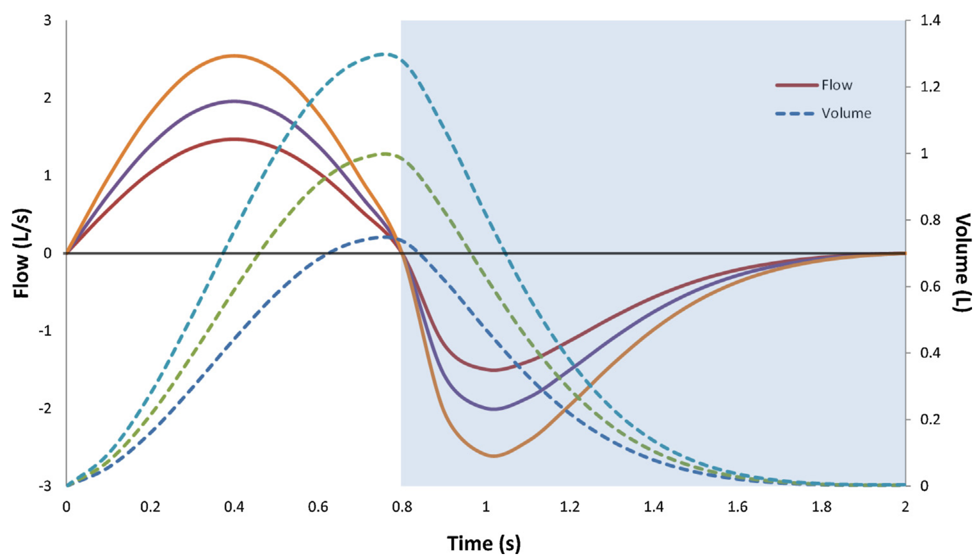

Fig. 2. Flows and volumes used in simulation. Positive flow is inspiration (unshaded region) and negative is expiration (shaded region). Increasing volume is inspiration and decreasing volume is expiration.

2. Materials and methods

2.1. Study design

A repeated measures observational study was performed. Using known mechanical sources of flow and metabolic gases, V_T, fR, $\dot{V}O_2$ and $\dot{V}CO_2$ measurements were taken during NIV at varying levels of pressure support (PS) and were compared to measurements taken without NIV.

2.2. Protocol

2.2.1. Ventilatory variables

To test volume measurement accuracy, an ASL5000 mechanical piston respiratory simulator (IngMar Medical Ltd., Pittsburgh, PA USA) was used and was set up with sensors for the measurement of V_T and fR (Fig. 1). Using Microsoft Excel and computer software accompanying the ASL5000, a predefined breath waveform template was produced. This template was then scaled in time (equivalent to fR) and amplitude (equivalent to V_T) to provide a series of breaths with V_T ranging from 100 to 1300 mL, fR from 20 to 30 breaths/minute resulting in a minute ventilations between 5 and 40 L/min (Fig. 2). The piston was configured to replay the predefined template without response to PS provided by the ventilator. Twenty template breaths at each V_T and fR were run before immediately proceeding to the next set template. The loop of scaled template breaths was run five times within each test. Each test was performed without NIV at atmospheric pressure and then with NIV at different levels of PS. Pressure support was tested with a constant end-expiratory pressure (EEP) of 5 cm H_2O and increasing inspiratory pressures that resulted in PS of 2, 5, 10, 15 and 20 cmH_2O above the EEP. Mean and standard deviation (SD) were calculated from all measurement points for analysis of the limits of agreement and % error by Bland-Altman methods (Bland and Altman, 1986).

2.2.2. Metabolic variables

A metabolic simulator (GESV, Medgraphics, USA) was used to validate the metabolic variables with and without NIV (Fig. 3) (Huszczuk et al., 1990). Three levels of oxygen consumption were available from the metabolic simulator (low, medium and high), each with a corresponding fR, $V_{T,}$ $\dot{V}O_2$ and $\dot{V}CO_2$. Tidal volume and fR settings corresponded to 1000 mL at 10 breaths per minute (b/min), 2000 mL at 20 b/min and 1500 mL at 40 b/min. Precision mixed gas with a carbon dioxide content of 21% and balanced nitrogen content (BOC Gases, Australia) was input at a fixed flow rate for each setting of the simulator. Each setting was run for 60 s all breaths recorded at each setting were averaged for comparison and repeated five times. $\dot{V}O_2$ and $\dot{V}CO_2$ measurements without NIV and with NIV at each level of PS were analysed by the same Bland-Altman methods as the ventilatory variables.

2.3. Cardiopulmonary exercise testing equipment

The K4b2 (COSMED, S.r.l., Rome, Italy) was used to measure V_T, fR, $\dot{V}O_2$ and $\dot{V}CO_2$, and was calibrated immediately before each test according to the manufacturer's guidelines using a four-step process (Cosmed, 2002). First, a room-air calibration was completed to set the sensor offset to atmospheric values of oxygen and carbon dioxide. Then, a reference gas calibration with a known gas concentration (5% carbon dioxide, 16% oxygen and balance nitrogen) was used to provide a second point of offset for the oxygen and carbon dioxide sensors. Thirdly, a computer-controlled, mechan-