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PJBS

ISSN 1028-8880

Pakistan Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences 5(1): 104-106, 2002

Transthoracic Bioimpedance Measurement of Cardiac Responses to Maximal Cycle Exercise in Healthy Adult Females

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Abstract: The purpose of this study was to test the utility of transthoracic electrical bioimpedance (TEB) in evaluating cardiac responses to maximal cycle exercise in healthy adult females. Thirty college women (age 23.8± 3.9 yrs.), following a baseline resting evaluation, performed an upright maximal cycle ergometer test until exhaustion. Throughout testing, cardiac output (CO) and oxygen consumption were measured simultaneously by transthoracic bioimpedance cardiography (NCCOM3–R7, BoMed, Irvine, CA) and open circuit spirometry indirect calorimetry (OCM2, Physiodyne, Farmingdale, NY), respectively. Satisfactory CO readings were obtained throughout exercise in 26 of 30 subjects and they were highly related to directly measured oxygen uptake (mean individual r= 0.97, SD= 0.03). However, absolute CO values were higher when compared with previous studies using other standard invasive methodologies. It is concluded that TEB can be a useful, safe and non-invasive technique to measure relative changes in CO to maximal cycle exercise in healthy adult females.

Key words: Transthoracic bioimpedance, cardiac output, oxygen uptake, stroke volume

Introduction

An assessment of the pumping activity of the heart offers information of critical importance for evaluating the functional status of the human circulatory system. While a variety of standard methods have been developed over the years and are now widely recognized for use to evaluate cardiac output (CO), most of them, such as dye dilution, thermodilution and the direct Fick technique, require invasive procedures that greatly limit their utility (Moore *et al.*, 1992). The need for an alternative method that is relatively simple to use, safe, and noninvasive has led some researchers to study how changes in thoracic electrical impedance during the cardiac cycle are related to the stroke volume ejection of blood during cardiac systole. Termed transthoracic bioimpedance cardiography (TEB), this technique has emerged as a promising, yet sometimes still controversial, approach to evaluate human cardiac performance for a wide variety of clinical and scientific research purposes (Jensen *et al.*, 1995; Miles *et al.*, 1993; World, 1990).

The validity and reliability of TEB both at rest and during exercise has previously been examined by comparing CO values derived by thoracic impedance with those values obtained by standard invasive methods (Jensen, *et al.*, 1995). In addition, TEB findings have been compared to findings of other noninvasive techniques such as carbon dioxide rebreathing (Moore *et al.*, 1992) and doppler echocardiography (Huang *et al.*, 1990). Since CO is linearly and predictably related to oxygen uptake (VO_2) in healthy subjects (Astrand *et al.*, 1964), one reasonable approach has also been to use measured VO_2 as the standard by which to determine the accuracy of thoracic impedance derived CO values (Moore *et al.*, 1992; Rowland *et al.*, 1989).

Among a number of different TEB instruments that have been developed to date, the most advanced is the NCCOM3-R7 cardiograph (BoMed, Irvine, CA), which incorporates the Sramek-Bernstein equation to estimate stroke volume (World, 1990). Previously, Rowland *et al.* (1989) employed the NCCOM3-R7 to evaluate the cardiac responses to maximal cycle exercise in healthy adult males. Their findings revealed that thoracic impedance derived CO values were closely related to VO_2 and absolute resting and peak CO values were consistent with results using other methodologies. However, while it has long been proposed that important anthropometric and physiological differences between men and women exist which may affect the accuracy of thoracic impedance derived CO measures (Frey *et al.*, 1982), to our knowledge, none of the studies so far have specifically examined the applicability of the NCCOM3-R7 for use in normal females. Therefore, this study served to evaluate cardiac responses with the NCCOM3-R7 impedance cardiograph at rest and during maximal cycle exercise in healthy adult females and to compare these findings with the related literature.

Materials and Methods

Thirty female college students of ages between eighteen and thirty five years (mean 23.8± 3.9) participated in the study. All subjects were initially screened using a standard health/medical history questionnaire. Only apparently healthy individuals who provided a written informed consent were allowed to take part in the investigation. The experimental research procedures underlying this study were reviewed and approved by the Institutional Human Investigation Committee before the start of project.

The subjects' baseline cardiac responses and VO_2 were measured at rest for five minutes during the initial part of an experimental test session. During the second phase, a continuous graded maximal exercise test was performed on an upright, mechanically braked cycle ergometer (Model 818, Monark) with the seat height adjusted for leg length. For that purpose, the initial workload of 50 watts was followed by increments of 25 watts at 3-minute intervals until subjects reached voluntary exhaustion or failed to keep up with the requirement to maintain a 50 rpm cadence. Simultaneous cardiac responses and VO_2 values were obtained as the average of the last three minutes of data acquisition from the five minutes baseline rest evaluation and the mean of the last minute at each sub-maximal workload during exercise. Maximal exercise values were the average of the last minute prior to exhaustion prorated for partially completed minutes.

Oxygen uptake was measured by standard open circuit spirometry indirect calorimetry methods. For that purpose, subjects were connected via respiratory tubing and a low resistance, large 2-way breathing valve (Series 2700, Hans Rudolph, Kansas City, MO) to an AMETEK metabolic cart (OCM2, Physiodyne, Farmingdale, NY). Prior to each trial, the model S-3A/I oxygen and model CD-3A carbon dioxide analyzers of this respiratory gas analysis system were calibrated using a primary standard medical gas mixture of known concentrations. All instruments interfaced an IBM computer, which recorded and computed respiratory gas parameters continuously.

Changes in electrical impedance of the thorax are created by alternations in blood volume and velocity and these changes can be related mathematically to stroke volume. The NCCOM3-R7 cardiograph measures impedance changes in response to the administration of a small electrical current and then calculates SV according to the Sramek-Bernstein equation (World, 1990). Four specially designed silver/silver chloride dual ECG electrodes were applied to predetermined sites as per the manufacturer's guidelines. The upper group of two dual ECG electrodes was placed on either side of the root of the neck and the lower group was placed on either side of the thorax at the level of the xiphoid process along the mid-axillary line. An additional pair of electrodes was applied to the anterior chest wall at the extremities of the anticipated axis of ventricular depolarization. These electrodes were connected to a series of patient leads, which interfaced with the NCCOM3-R7 cardiac monitor.

The NCCOM3-R7 allows for a simultaneous monitoring of not only cardiac output, stroke volume, and heart rate (HR), but also estimates a variety of other cardiodynamic parameters including peak flow, ejection fraction, end-diastolic volume, index of contractility, thoracic fluid index, acceleration index, ventricular ejection time, ejection ratio, and systolic time ratio. It can perform this task either in "fast" mode (beat-by-beat, for six parameters only) or can display the mean values of each variable, over 16 acceptable heartbeats, in the "slow" mode. It also has the function to index selected data by body weight (BW) and body surface area (BSA). Following the manufacturer's guidelines, the "slow" mode was used in the current study since this mode has the tendency to statistically balance out erroneous TEB data caused by transitory thoracic motion artifacts during exercise. Moreover, subjects were asked to minimize any unnecessary thoracic movements during testing as much as possible.

Impedance derived measures of SV, HR, and CO were used as raw data for the statistical analysis. Further, cardiac index (CI) and stroke volume index (SVI) values were computed from measures of CO and SV by correcting them to body surface area (BSA) according to the formula byBois and Bois (1916):

$$\text{BSA (m}^2\text{)} = \text{Weight (kg)}^{0.425} \times \text{Height (cm)}^{0.725} \times 0.007184$$

The relationship between CO and VO_2 for the group's response data was determined using linear regression. Since the evaluation of cardiac responses based upon a subject's individual data is often more informative than a group's mean response (Miles *et al.*, 1993), the relationship between CO and VO_2 for each individual subject's data was assessed by using Pearson product-moment correlation coefficients (r) to determine individual "r" values. These values were subsequently averaged to determine a mean individual "r" value. Cardiac responses and VO_2 measurements were summarized using descriptive statistics (M± SD). Statistical analyses were performed using SPSS (Statistical Package for Social Services software, release 4.0 Mac).

Results

Satisfactory impedance derived CO readings were obtained in 26 out of 30 female subjects (86.7%) at rest and during exercise. For individual's data the mean individual correlation coefficient between CO (L/min) and VO_2 (L/min) was 0.97 (SD= 0.03). For the group's response data, a positive linear relationship was obtained between CO (L/min) and VO_2 (L/min) with an r of 0.84, an R^2 of 0.71 (SEE= 3.76), an intercept of 4.14 (± 0.63) and a slope of 8.37 (± 0.41). In addition, when CO was indexed by BSA to account for the variation in body size, a similar close and linear relationship between CI and VO_2 was observed (r= 0.82, R^2= 0.67, SEE = 2.34).

The 26 out of 30 subjects with complete test data had a mean resting CO of 6.2 L/min (± 1.3) and a corresponding CI of 3.7 L/min/m² (± 0.7). These values at maximal exercise were 23.1 L/min (± 4.9), and 13.9 L/min/m² (± 2.5), respectively. The average resting SV rose from 77.8 ml/beat (± 19.9) at rest to 127.7 ml/beat (± 28.4) at exhaustion. The mean resting SVI was 46.4 ml/m² (± 10.00) and 76.4 ml/m² (± 14.4) at peak exercise. The mean resting HR of the subjects was 81.2 beats/min (± 13.8), which rose to 183 beats/min (± 11.1) at the end of the exercise test. The VO_2 values at rest and at peak exercise were 0.25 L/min (± 0.05), and 2.2 L/min (± 0.44), respectively.

Discussion

The present study generally supports the use of the NCCOM3-R7 impedance cardiograph for assessing cardiac responses to maximal cycle exercise in healthy adult females. Satisfactory cardiac response readings were obtained in 26 out of 30 subjects (86.7%). These findings closely match those of Rowland *et al.* (1989) who obtained satisfactory CO values to maximal cycle exercise in 18 of 21 male subjects (85.7%). Data for four subjects could not be recorded due to the absence or erroneous SV values which were most likely caused by motion or respiration artifact, a voltage dependent inability to always successfully detect R waves in some subjects, and exercise induced perspiration that may have interfered with the skin-electrode interface (Rowland *et al.*, 1989; Yakimets and Jensen, 1995).

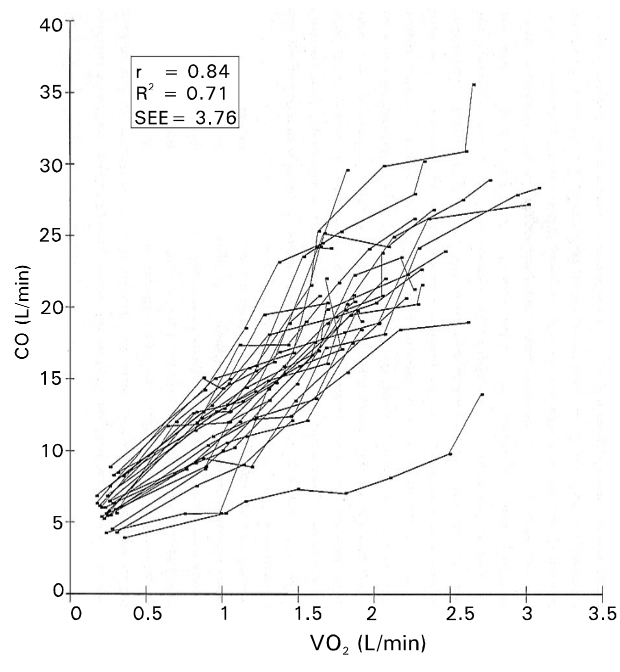

Fig. 1: Individual plots of relationship between cardiac output and oxygen uptake to graded maximal cycle exercise (n= 26).

This study revealed an r value of 0.84 for the group's response data and a mean individual's r value of 0.97 (SD= 0.03) for the individual's data between CO and VO_2. The observed positive linear relationship between CO and VO_2 is illustrated in Fig. 1 for all 26 subjects on whom completed measurements were obtained from rest to maximal exercise.

Rowland *et al.* (1989) previously also reported a close and linear positive relationship between impedance derived CO and $V0_2$ (r= 0.93) using the NCCOM3-R7 during progressive maximal cycling exercise in healthy adult males. However, while these researchers concluded that their mean absolute resting and peak CO values were similar to corresponding values obtained with other criterion methodologies in similar groups of men, a comparison of the present findings in females to other studies from the scientific literature bring into question the absolute accuracy of the impedance derived CO values obtained.

Specifically, this study revealed mean absolute resting CO values of 6.2 L/min and maximal exercise values of 23.1 L/min. These values are consistently higher when compared to those of similar studies using other reference methodologies in females (Astrand *et al.*, 1964; Sullivan *et al.*, 1991). Huang *et al.* (1990) presented that, while the Sramek-Bernstein equation provides SV values in males in the predicted range, it overestimates SV by approximately 15% in females. When the resting and mean exercise CO values obtained in the present study are reduced by 15%, they are similar to the values obtained by Astrand *et al.* (1964) who employed the same graded exercise protocol and dye dilution technique to assess cardiac responses. The same is seen when mean resting and maximal exercise CI values (3.7 L/min/m^2 and 13.9 L/min/m^2, respectively) obtained in the present study are compared to the values reported by Sullivan *et al.* (1991) who utilized the direct Fick method to obtain CI values (3.3 L/min/m^2 at rest and 9.4 L/min/m^2 at maximal exercise) in female subjects. It has long been hypothesized that certain gender-specific biological characteristics may cause differences in thoracic impedance and affect CO results (Frey *et al.*, 1982). Fat is more resistive to current than muscle and individuals with a smaller thoracic circumference have higher resistance to current (Miles and Gotshall, 1989). Since the NCCOM3-R7 incorporates the Sramek-Bernstein equation for estimating SV, dependence on body habitus may also affect the accuracy of the values obtained (Jensen *et al.*, 1995). Notwithstanding these limitations to the utility of the TEB data obtained, the present findings and those of others (Miles *et al.*, 1993; Rowland *et al.*, 1989) provide evidence that this technique can be used to estimate directional changes of CO up to maximal exercise.

In conclusion, relative changes in cardiac responses in healthy females can be adequately measured with the NCCOM3-R7 cardiograph. The equipment is non-invasive, safe and simple to use, and provides valuable information regarding reserve cardiac capacity. A comparison with other studies from the available literature provides indirect evidence, though, which demonstrates that absolute CO values are higher than corresponding values obtained with other standard reference methodologies.

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