EVALUATION OF A SIMPLE ESTIMATION METHOD FOR THE DERIVATION OF CARDIAC OUTPUT FROM ARTERIAL BLOOD PRESSURE AND HEART RATE

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ABSTRACT

Cardiac Output (CO) is an important hemodynamic index of blood flow from and to the heart. Numerous estimation methods have been developed and validated for obtaining CO in clinical applications; however, the invasive nature of these may preclude their utility in less controlled settings. Additionally, several of the available non-invasive applications feature algorithms which are computationally complex or proprietarily-restricted and may not be feasible in all research contexts, such as ambulatory investigations. Among the many simple mathematical transforms purported to estimate CO, a common approach has been to multiply the stroke volume (SV) by the heart rate (HR), where stroke volume is obtained by multiplying the pulse pressure (PP) by a constant value (k). Contemporary interpretations have identified k = 2 as the ideal multiplier; however there is some controversy regarding the origin of this factor as well as the reliability of the resulting estimate. In the present study we evaluated this simple technique using baseline beat-to-beat blood pressure data from 67 young (mean age = 20.04 ± 2.8 years), healthy men (n = 30) and women (n = 37). Using Modelflow-derived CO as a reference, estimated CO (CO_{est}) was calculated from the mean Systolic and Diastolic blood pressures and the heart rate. Overall, the correlation between CO & CO_{est} was moderate ($r = .60$, $p < .001$). This association was stronger in men ($r = .70$, $p < .001$) compared to women ($r = .54$, $p < .001$). Bland-Altman analysis confirmed this pattern as 97% of cases for men fell within the limits of agreement. Overall, our results indicate that under resting conditions this derivation is comparable to the Modelflow estimate and seemingly more consistent in men compared to women.

Keywords: Cardiac Output, Pulse Pressure, Heart Rate

INTRODUCTION

Cardiac Output (CO | L/min) is an important hemodynamic index of blood flow from and to the heart. Compensatory changes in CO occur in response to a change in tissue oxygen demand, such as the increase in CO typically seen during exercise. Importantly, a chronically elevated CO may also indicate improper organ functioning wherein the metabolic demands of the target tissue are not being adequately met. Thus, the ability to accurately monitor and track changes in CO is an important goal for clinicians and researchers, alike. Numerous estimation methods have been developed and validated for obtaining CO in clinical applications; however, the invasive nature of these may preclude their utility in less controlled or research settings.

Presented at Rocky Mountain Bioengineering Symposium & International ISA Biomedical Sciences Instrumentation Symposium
Hosted by Virginia Tech - Wake Forest School of Biomedical Engineering and Sciences Blacksburg, VA, 22-24 March 2012

Additionally, several of the available non-invasive applications feature algorithms which are computationally complex or proprietarily-restricted [1] and may not be feasible in all research contexts, such as ambulatory investigations.

CO is typically defined as the product of the volume of blood pumped with each heartbeat, or the stroke volume (SV) measured in milliliters (ml) multiplied by the heart rate (HR) in beats per minute (bpm) [Equation 1].

$$\textbf{CO (L/min)} = \textbf{SV (ml)} \times \textbf{HR (bpm)} \qquad \text{(eq.1)}$$

As early as 1904, medical researchers had developed equation-based estimates of CO that incorporated clinically-obtained measures of arterial blood pressure and pulse (heart) rate. A recent investigation found that one such index produced absolute estimates of CO with a standard deviation of error of one L/min compared to CO measured invasively using the thermodilution method [2].

Among the many simple mathematical transforms purported to estimate CO, one technique commonly used has been to multiply the stroke volume by the heart rate, where stroke volume is obtained by multiplying the pulse pressure (PP | mmHg), calculated as the mean systolic blood pressure (SBP | mmHg) minus the mean diastolic blood pressure (DBP| mmHg) [Equation 2], by a constant value (k) [Equation 3].

$$\textbf{PP(mmHg)} = \textbf{SBP (mmHg)} - \textbf{DBP (mmHg)} \qquad \text{(eq.2)}$$

$$\textbf{CO}_{\textbf{est}}\textbf{(L/min)} = [\textbf{k} \times \textbf{PP(mmHg)}] \times \textbf{HR (bpm)} \qquad \text{(eq.3)}$$

Contemporary interpretations have identified $k = 2$ as the ideal multiplier; however there is some controversy regarding the origin of this factor [3] as well as the reliability of the resulting estimate. Therefore, the goal of the present research was to evaluate the utility of this simple formula to provide valid estimates of CO relative to another validated non-invasive method.

METHODS

We evaluated this simple technique using beat-to-beat blood pressure (BP) data from 67 young, healthy men and women. Continuous beat-to-beat blood pressure was obtained during a resting baseline, standing (orthostatic challenge), a seated recovery, a reading task, an autobiographical anger recall (psychological stressor task) and a second recovery period. The duration of each task was approximately 5 minutes (see Hill et al., 2009 for full task descriptions, [4]).

Data were recorded using the Finometer® MIDI non-invasive blood pressure monitoring device (FMS Medical Systems, The Netherlands), which estimates CO using the Modelflow method based on a three-element Windkessel model which has been previously described (see Sollers et al., 2006, [5]) and shown to produce values comparable to those obtained via thermodilution [6]. To obtain CO_{est} values with a proper unit of measurement (i.e. liter per minute| L/min), a pressure-to-volume conversion was performed.

Where 1 millimeter of mercury (mmHg) is equivalent to 1 cubic centimeter (cm^3) or 1 milliliter (ml), and 1 ml is equal to .001 liters (L). Thus, by way of metric conversion k = 2 becomes k = .002.

$$\mathbf{CO_{est}(L/min) = [2 \times PP(mmHg)] \times HR(bpm)} \qquad \text{(eq.4)}$$

$$\mathbf{where,\ 1\ mmHg = 1\ cm^3 |\ 1\ cm^3 = 1\ ml}$$

$$\mathbf{and,\ 1\ ml = .001\ L}$$

$$\mathbf{Thus,\ CO_{est}(L/min) = [.002 \times PP(ml)] \times HR(bpm)}$$

The resulting value was then multiplied by the heart rate (HR) yielding an estimate of cardiac output (CO_{est}| L/min). Pearson's correlation (r) was used to evaluate the association between baseline cardiac output (CO) derived via the Finometer and the estimate (CO_{est}). Bland-Altman plots were constructed to further assess the level of agreement between Modelflow-derived CO and CO_{est} overall, as well as separately by gender [6].

RESULTS

Table 1. Total and subsample *n's*, means and standard deviations for resting beat-to-beat data.

M(SD)	Men	Women	Total
n	30	37	67
Age (yrs)	19.97 (2.0)	20.11 (3.4)	20.04 (2.8)
SBP (mmHg)	125.23 (15.55)[a]	116.54 (13.05)	120.33 (14.88)
DBP (mmHg)	69.54 (11.22)[a]	63.98 (9.73)	66.45 (10.71)
HR (bpm)	72.73 (9.80)	76.79 (11.03)	75.07 (10.62)
PP (mmHg)	55.69 (9.43)	52.56 (9.62)	53.88 (9.59)
CO (l/min)	6.07 (1.04)	5.82 (1.25)	5.94 (1.15)
CO_{est} (l/min)	7.81 (1.53)	7.93 (1.79)	7.87 (1.64)

[a] denotes significant difference $p < .05$

Participants were comparable in age, resting HR and PP. Males had significantly higher SBP and DBP compared to female participants. Males also exhibited higher baseline CO though interestingly, this difference was not statistically significant and this pattern was reversed when CO_{est} was considered.

Overall, CO_{est} was larger than CO obtained via the Modelflow method, suggesting that this procedure produces an inflated parameter estimate. Correlational analysis revealed a significant moderate correlation overall between CO and CO_{est} (Figure 1). Interestingly, the correlation between CO and CO_{est} was stronger in males (Figure 2) and was attenuated but remained significant in females (Figure 3).

The mean difference between CO and CO_{est} was -1.83 (1.3) overall, -1.59 (1.0) and -2.05 (1.5) for men and women, respectively. As shown in Figure 4, 62 (93%) of the cases fell completely within the limits of agreement in Bland-Altman analysis; five cases were at or below the lower 95% limit of agreement.

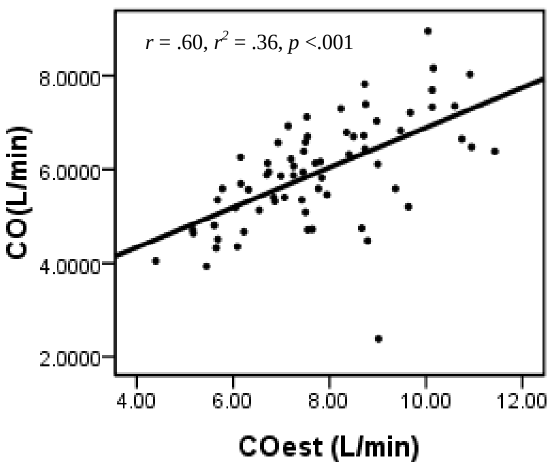

Figure 1: Scatterplot of CO & COest: All

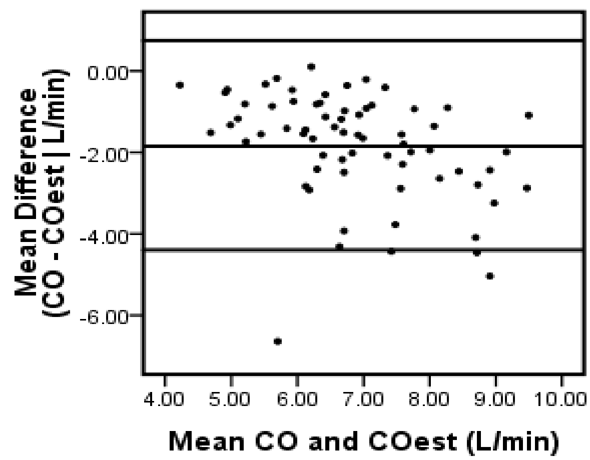

Figure 4: Bland-Altman plot: CO & COest: All

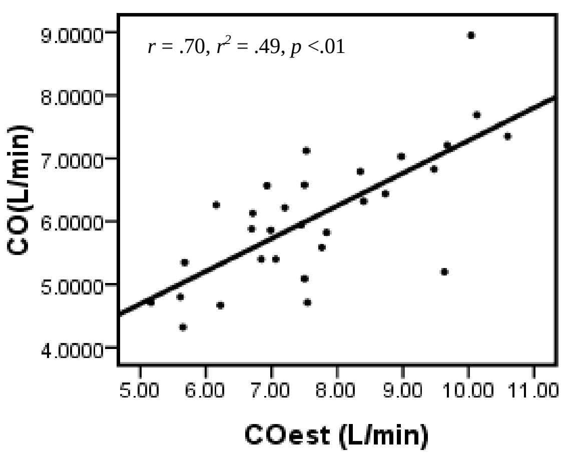

Figure 2: Scatterplot of CO & COest: Males

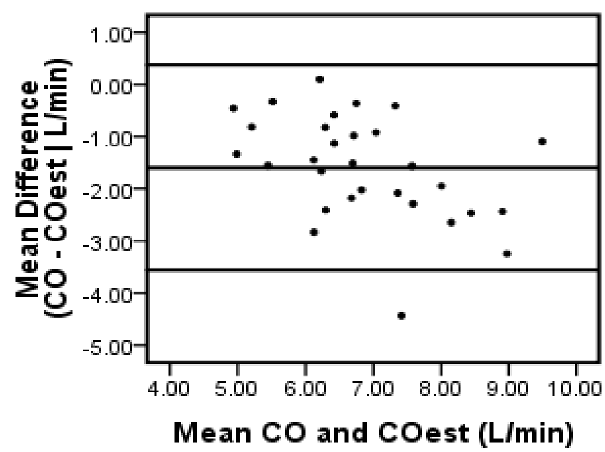

Figure 5: Bland-Altman plot: CO & COest: Males

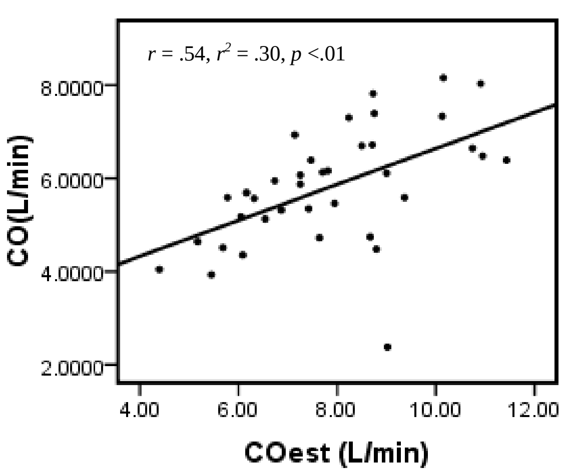

Figure 3: Scatterplot of CO & COest: Females

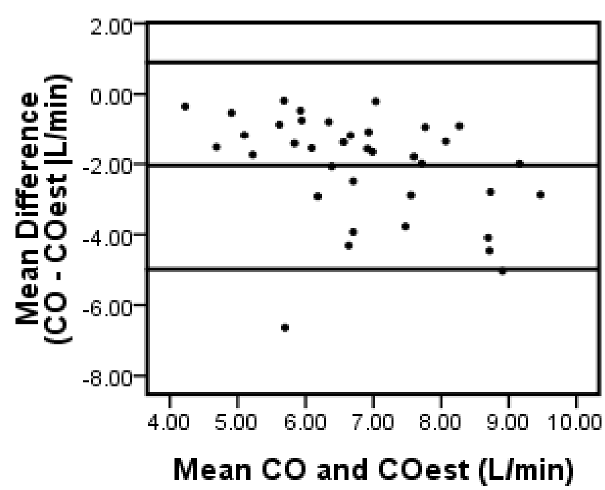

Figure 6: Bland-Altman plot: CO & COest: Females

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Analyses further confirmed that the association was stronger in men as 97% of cases fell within the 95% limits of agreement (Figure 5). 95% of cases for women also fell within the limits of agreement; two cases fell at or below the lower limit (Figure 6).

DISCUSSION

Based on these results, CO_{est} appears to provide a close approximation of CO obtained at rest. However, and as previously noted, CO changes in response to the body's demand for oxygen. Interestingly, it is unclear to what extent, if at all, k remains stable given a significant change in HR. We evaluated the generalizability of CO_{est} in tracking patterns of change in CO during tasks involving sustained physical and mental effort. For illustrative purposes, these data have been plotted in Figure 7.

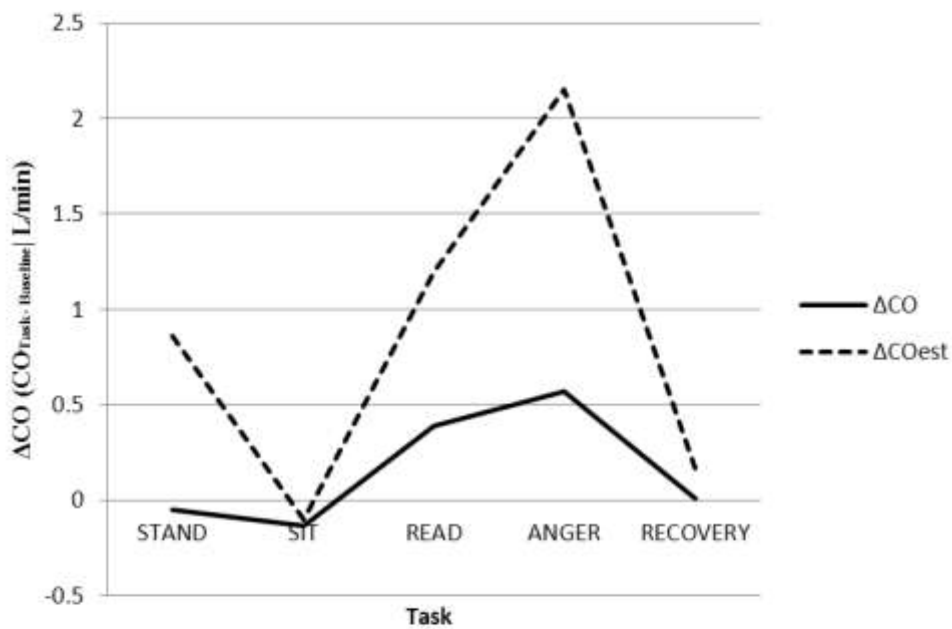

Figure 7: Difference Scores (Task – Baseline) for CO & CO_{est} across a series of laboratory tasks. Note: Plotted data represents averaged values across all subjects.

Difference scores were calculated as the mean value of CO (CO_{est}) for a given task minus the baseline value (i.e. $CO_{STAND} - CO_{BASELINE}$) and are denoted with a delta (Δ). As can be seen in Figure 7, our prior observation of a slight overestimation using the simple equation method (ΔCO_{est}, dashed line) was confirmed for tasks involving physical and mental activity. Importantly whereas the mean change values are overestimated by CO_{est}, CO_{est} does accurately track the group averaged directional change. Thus, relative increases and decreases in CO can be observed with both methods.

With the exception of the standing task, all tasks were completed in the seated position, so it is unlikely that posture can explain the observed differences between CO obtained with the Modelflow method and the CO_{est}. Moreover, for estimates obtained during the seated and recovery periods, the overall difference between ΔCO obtained via the Modelflow method and ΔCO_{est} is minimal.

Overall, the observed pattern supports the general notion that under resting conditions, CO_{est} appears to provide a reliable and relatively accurate parameter estimate; whereas, under conditions of physical or mental activity COest appears to be less stable.

CONCLUSIONS

We evaluated a simple equation-based estimate of cardiac output, obtained using SBP, DBP, HR and a constant value. Prior research has proposed that the equation [2ml x PP x HR], provides an accurate estimate of CO; however the origin of this formula is largely unknown. In our investigation, we examined this simple equation in comparison with CO obtained via a validated estimation method. Our results indicate that under resting conditions, CO_{est} is comparable to the Modelflow estimate and seemingly more consistent in men compared to women. This difference may reflect historical trends in which males were more likely to be research subjects than females, but also suggests that a relatively accurate and reliable proxy for CO has been available for over a century.

Thus, CO_{est} may be an inexpensive and computationally simple method to estimate CO and its change that might be useful for investigators conducting research in situations where other methods such as thermodilution or Modelflow are not feasible or practical. In addition, it may be an inexpensive alternative to extend the capabilities of older, automated as well as ambulatory BP devices that only provide BP and HR. Furthermore, it may also be possible to obtain additional information from archival data in which only BP and HR are available. Lastly, given the dynamic compensatory interaction of CO and vascular resistance in the regulation of blood pressure, future research should evaluate whether CO_{est} may also be useful in obtaining a valid estimate of vascular resistance and/or additional hemodynamic parameters.

ACKNOWLEDGMENTS

We would like to thank all of the participants at The Ohio State University.

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