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The Effect of Signal Quality on Six Cardiac Output Estimators

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Abstract

The effect of signal quality on the accuracy of cardiac output (CO) estimation from arterial blood pressure (ABP) was evaluated using data from the MIMIC II database. Thermodilution CO (TCO) was the gold standard. A total of 121 records with 1,497 TCO measurements were used. Six lumped-parameter and systolic area CO estimators were tested, using ABP features and a robust heart rate (HR) estimate. Signal quality indices for ABP and HR were calculated using previously described metrics. For retrospective analysis, results showed that the Liljestrand method yielded the lowest error for all levels of signal quality. Increasing signal quality decreased error and only marginally reduced the amount of available data, as a signal quality level of 90% preserved sufficient data for almost continuous CO estimation. At the recommended signal quality thresholds, the lowest gross root mean square normalized error (RMSNE) was found to be 15.4% (or 0.74 L/min) and average RMSNE was 13.7% (0.71 L/min).

1. Introduction

Cardiac output (CO) is useful in assessing patients with compromised cardiovascular performance. In intensive care units (ICU), the thermodilution cardiac output (TCO) method [1] is the “gold standard” commonly used, whereby a bolus of cold fluid is injected into the right atrium. Temperature change is monitored at the pulmonary artery using a thermistor-tipped Swan-Ganz catheter. Currently, cardiac output is monitored only intermittently and can only be performed in well-equipped environments such as ICUs or cardiac catheterization labs. Its invasive nature increases the potential for complications, including higher risk of infection and sepsis and greater possibilities of morbidity and mortality [2].

The accuracy of CO estimation from ABP has been well studied in the past [3]. The estimators evaluated in this study rely on lumped-parameter or pressure-area methods that estimate stroke volume and use heart rate (HR) to obtain CO. Therefore, CO estimation requires: 1) reliable ABP measurements, 2) reliable HR measurements, and 3)

an accurate CO estimator method. However, in real clinical settings, ABP and HR measurements are prone to artifacts due to patient movement, sensor disconnections, arterial line blockage, or mechanical devices such as intra-aortic balloon pumps that can result in misleading CO estimates. To avoid false CO estimates, it is necessary to reject ABP and HR data that is corrupted by noise and artifact by using a signal quality index (SQI).

This article examines the impact of varying minimum signal quality thresholds on the accuracy of 6 CO estimators in a retrospective analysis.

2. Methods

The cardiac output estimation and evaluation procedure is outlined in Fig. 1. ABP data was taken from records in the Multi-Parameter Intelligent Patient Monitoring for Intensive Care (MIMIC) II database [4]. A 121-record subset was found for which continuous ABP waveforms and simultaneous TCO measurements were available. Records that had less than 5 TCO measurements or had intra-aortic balloon pumps were not included in this study. ABP waveforms were sampled at 125 Hz with 8-bit quantization. TCO was available intermittently with a temporal resolution of 1 minute. Each non-overlapping 10 seconds of data yielded a HR(h_r) estimate together with an SQI for ABP and HR (ABPSQI and HRSQI respectively) ranging from 0 (bad) to 100 (good), as detailed in Li *et al.* [5]. Blood pressure parameters extracted included diastolic blood pressure (P_d), mean blood pressure (P_m), systolic blood pressure (P_s), pulse pressure ($P_p = P_s - P_d$), and pressure area during systole (A_s).

The onset of each ABP pulse was detected using an implementation of Zong *et al.*'s *wabp* algorithm [6].

2.1. SQI correction

A cardiac output estimate was produced for a 1-minute window preceding each TCO measurement when sufficient reliable ABP and HR data were available. Signal quality indices were used as metrics to determine whether or not sufficient clean data was present within the window.

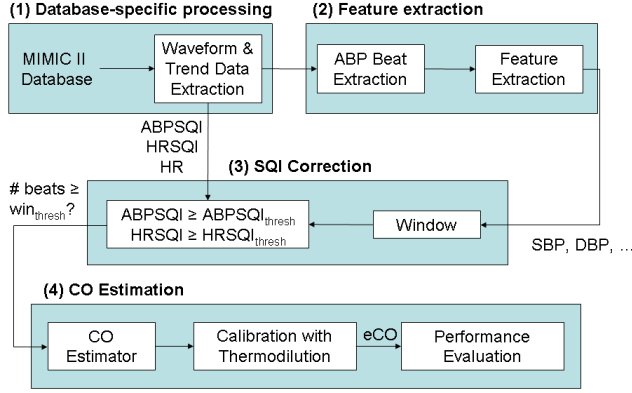


Figure 1. Cardiac output estimation and evaluation procedure.

HR, HRSQI, and ABPSQI, sampled at 0.1 Hz, were linearly interpolated for each beat. For a beat to be considered “good”, both heart rate and blood pressure had to pass thresholds such that $HRSQI \geq HRSQI_{\text{thresh}}$ and $ABPSQI \geq ABPSQI_{\text{thresh}}$.

The extracted features from the high quality beats were median filtered over the 1-minute window before being passed to the CO estimation algorithms. No estimates were made for 1-minute sections with less than 6 good beats, approximately 10% of the window.

CO estimator	$CO = k \cdot \text{below}$
Mean ABP	P_m
Windkessel [7]	$P_p \cdot h_r$
Herd [8]	$(P_m - P_d) \cdot h_r$
Liljestrand [9]	$\left(\frac{P_p}{P_s + P_d}\right) \cdot h_r$
Systolic area [10]	$A_s \cdot h_r$
Wesseling [11]	$(163 + h_r - 0.48 \cdot P_m) \cdot A_s \cdot h_r$

Table 1. Cardiac Output Estimators.

2.2. CO estimation

The CO estimators evaluated in this study are listed in Table 1, separated into 4 lumped-parameter models and 2 systolic-area methods. The proportionality constant reflects arterial compliance and peripheral resistance factors that cannot be calculated using arterial blood pressure waveforms without additional calibration data. A global calibration method was derived using a least squares estimate between TCO points and their respective uncalibrated CO estimates in the 1-minute windows preceding each measurement.

We now define \mathbf{x} as the uncalibrated cardiac output (UCO), \mathbf{y} as the calibrated cardiac output (ECO), \mathbf{r} as TCO, and k as the calibration constant. For a record con-

taining n TCO measurements, the calibration constant was calculated as follows:

$$\begin{aligned} \text{TCO} \quad \mathbf{r} &= [r_1, r_2, \dots, r_n]' \\ \text{UCO} \quad \mathbf{x} &= [x_1, x_2, \dots, x_n]' \\ \text{ECO} \quad \mathbf{y} &= k\mathbf{x} \end{aligned}$$

$$\text{where } k = \frac{\mathbf{r}'\mathbf{x}}{\mathbf{x}'\mathbf{x}}.$$

3. Results

3.1. Error criteria

CO estimates were compared to TCO to determine the accuracy of the estimates. A root mean square normalized error (RMSNE) criterion was used. For each record s with n_s comparable TCO points, the RMSNE for the ECO for the record, RMSNE_s , in units of percent is:

$$\text{RMSNE}_s = \sqrt{\frac{1}{n_s} \sum_{n=1}^{n_s} \left(\frac{100(\text{TCO}_n - \text{ECO}_n)}{\text{TCO}_n} \right)^2}$$

To evaluate the accuracy of the estimates across all records, the RMSNE_s were averaged to obtain an *average* RMSNE, RMSNE_a . The data set has a total of N comparable thermodilution points across all records, where $N = \sum_s n_s$. For all records s , the RMSNE_a is:

$$\text{RMSNE}_a = \frac{1}{N} \sum_s \text{RMSNE}_s$$

However, RMSNE_a can be skewed in a particular direction if n_s for each record is not taken into account, particularly if a record has a greater n_s and/or is more error-prone. To account for these variations, a *gross* RMSNE measure, RMSNE_g , is also used. This error metric is a weighted mean of the individual RMSNE_s according to n_s . The gross RMSNE, RMSNE_g , is:

$$\text{RMSNE}_g = \sqrt{\frac{1}{N} \sum_s n_s (\text{RMSNE}_s^2)}$$

RMSNE is in units of percent. If each difference between TCO and ECO in RMSNE is not normalized by TCO, a root mean square error (RMSE) can be obtained in liters per minute as follows:

$$\text{RMSE}_s = \sqrt{\frac{1}{n_s} \sum_{n=1}^{n_s} (\text{TCO}_n - \text{ECO}_n)^2}$$

Analogous average and gross RMSEs can be calculated for each data set. However, results using both RMSNE and RMSE generally indicate the same trends. RMSNE tends to overweight errors for lower TCO values, which are when errors in CO estimates may have the most clinical impact, so only RMSNE values are reported for all data sets in this paper.

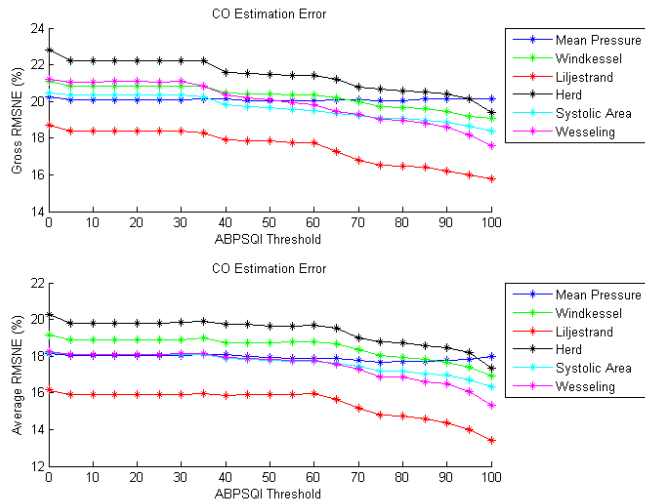


Figure 2. Estimator comparison at different ABPSQI thresholds, with HRSQI fixed at 50.

3.2. Estimator comparison

With the HRSQI threshold fixed at 50 (as per Li *et al.* [5]), the 6 CO estimators were compared at different ABPSQI thresholds. Fig. 2 illustrates the results. The Liljestrand estimator yields the lowest errors at all ABPSQI thresholds, while the Herd estimator generally yields the highest errors. The mean pressure method changes little with varying ABPSQI thresholds, and considering its simplicity, yields lower errors at low ABPSQI thresholds than most estimators. The Liljestrand and Wesseling methods are the most sensitive to ABP signal quality, with lower errors at higher ABPSQI thresholds. The Windkessel, Herd, and systolic area methods show higher accuracy as ABPSQI threshold is increased as well.

3.3. HRSQI and ABPSQI thresholds

The effects of varying both ABPSQI and HRSQI thresholds on the best (Liljestrand) method were then evaluated. Fig. 3 illustrates the effect of requiring minimum ABPSQI and HRSQI values for a particular record, in this case using an ABPSQI threshold of 90 and HRSQI threshold of 50. Sharp spikes in the CO estimate are removed or reduced with signal quality thresholding, as these are most likely due to artifacts in the data recordings. Furthermore, sudden drops or rises are mitigated, such as in the section at 1900 to 2000 minutes.

Fig. 4 illustrates the results using the RMSNE error criteria. As signal quality thresholds become more stringent, error decreases. By increasing either the HRSQI or ABPSQI threshold, a lower error for both the gross and average RMSNE is achieved. Beats that have questionable reliability

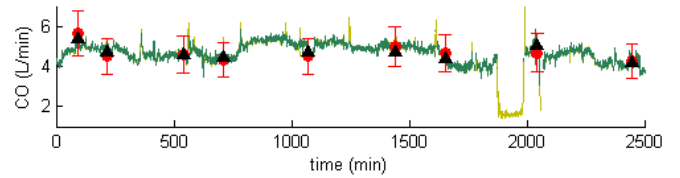


Figure 3. CO estimate for Case ID a40006 with SQI correction using the Liljestrand method. Estimated CO is shown in green, with artifactual areas detected with SQI metrics in beige. The red circles represent TCO measurements with error bars of 20%, and the CO estimates at those points are indicated with black triangles.

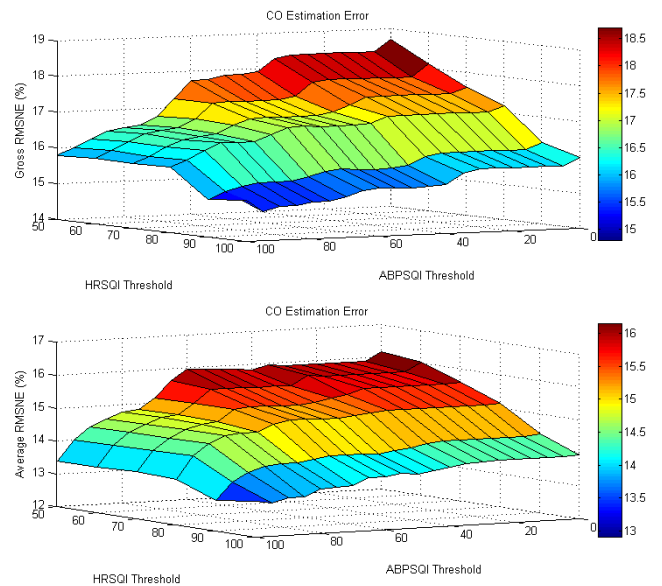


Figure 4. Errors at different ABPSQI and HRSQI thresholds using the RMSNE error criteria.

are excluded from estimation, so the remaining beats should more accurately reflect the underlying physiological condition. However, as SQI requirements become more stringent, fewer TCO points are used in calculating RMSNE, since fewer windows pass the SQI requirements and fewer CO estimates are generated. The number of TCO-ECO pairs available for comparison are shown in Fig. 5.

The effect of ABPSQI threshold is more evident when HRSQI threshold is lower. The error decreased up to 14% by varying HRSQI, and as ABPSQI was increased, a similar decrease in error was also observed. A trade off occurs between accuracy and availability of CO estimates, since increased stringency excludes more data from participating in the estimation process. However, even at $HRSQI \geq 90$ and $ABPSQI \geq 90$, more than 80% of the data is still available to generate CO estimates. These experiments were repeated using windows of up to 7 minute lengths (preced-

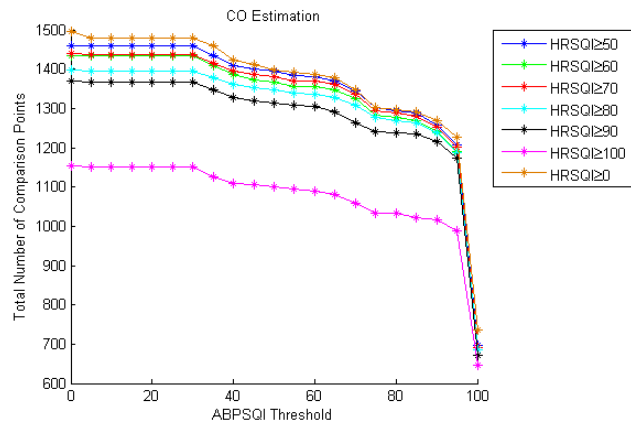


Figure 5. Data availability at different ABPSQI and HRSQI thresholds.

ing the TCO measurement) with only a small increase in the error.

4. Discussion and conclusions

For all signal quality thresholds investigated, the Liljestrand method yielded the lowest error for retrospective calibration using all available TCOs. Note for online CO estimation, accuracy depends on temporal proximity to TCO data and recent hemodynamic variability. If sufficient TCO calibration points are available, we recommend employing the Liljestrand estimator using 6 or more beats with HRSQIs greater than 90 and ABPSQIs greater than 90 in 1-minute windows. With these parameters, RMSNE_g is 15.4% (0.74 L/min) and RMSNE_a is 13.7% (0.71 L/min). These results are within the error range of the gold standard TCO itself (10-20% or 0.5-1 L/min for a standard 5 L/min CO) [12]. 80% of our ICU data is of high enough quality to make such an estimate, corresponding to throwing away only one in every five minutes of data, and an almost continuous CO estimate can be made. Estimation error decreases if SQI thresholds are increased further, but only 43% of the data is of sufficient quality at HRSQIs and ABPSQIs of 100. Thus, the tradeoff between availability and further accuracy of estimates will depend on the clinical consequences of erroneous estimates.

While ABPSQI and HRSQI are effective at eliminating sudden distortions in ABP and HR caused by artifact, slowly-changing artifacts such as ABP damping are poorly detected. Modifications of SQI measures to account for these types of artifacts will increase clinical utility of CO estimates from ABP.

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