Non Invasive Real Time Estimation of Cardiac Output Through Analysis of Arterial Waveforms

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Abstract
Cardiac output (CO) is defined as the volume of blood pumped out of the heart per unit time, typically in L/min. It is either directly measured or determined by calculating the product of Stroke Volume and Heart Rate, factors which are traditionally measured through an invasive approach in an ICU, such as a catheter, arterial line, etc. However, a non-invasive approach to calculate CO is far more convenient, cheaper, and does not require setup or calibration from a medical professional. In this paper, I 1) Introduce a non-invasive sensor technology which can estimate a variety of medical blood-flow related values in real time, 2) Propose several ways to arrive at a viable measurement of real-time CO, and 3) Compare the results and come to a conclusion of whether there is an accurate method, and if so, which method is the most accurate.

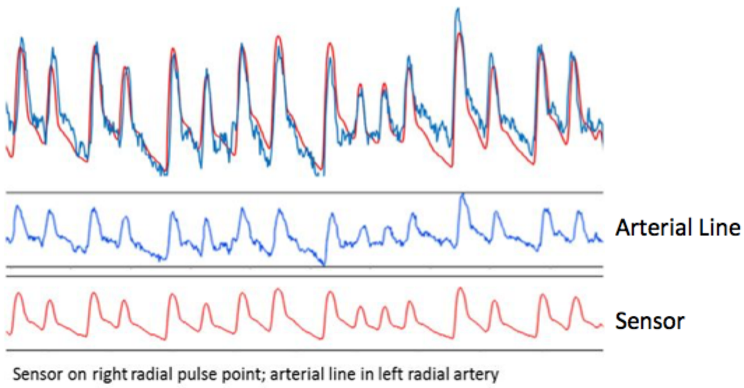
1. Introduction
We have developed a new device to continuously and noninvasively infer the blood pressure of neonates through changes in capacitance measured over a pulse point such as a radial artery.

Patient characteristics: Our IRB-approved study evaluated 11 neonates less than 1 week old with umbilical catheters.

Device Design: The small, lightweight (<12g), paper-thin (~50µm), flexible, and extremely sensitive array of 4 sensors is incorporated into a disposable stretchable band that wraps around the wrist or foot (**Fig 1.1**). Reusable lightweight, low-power electronics acquire pulse waveform data and stream it in real-time to a custom Android application or bedside monitor. BP values are extracted from the cNIBP pulse waveform data in post-processing.

Figure 1.1: [Small form factor wrist/foot worn continuous non-invasive BP sensor in neonates]

This small, lightweight device does not require intimate skin contact. It is low cost, easy to use and less perturbing to the patient than an IAL or other non-invasive cNIBP options. In general, cNIBP Sensor data (blue) correlates well with IAL data (red) taken simultaneously (**Fig. 1.2**).
Figure 1.2: [Raw cNIBP radial sensor data (blue) scaled to overlay radial arterial line data (red) taken simultaneously on the opposite wrist]



2. Methods

2.1 Feature Extraction

BP Derivation: The Android application uses proprietary and highly-efficient artificial neural network (ANN) algorithms to derive blood pressure values (listed in **Table 2.1**) from measured pulse waveform data measured in real-time.

Accuracy metrics: Since the eventual goal is to apply for FDA clearance, we chose to aim to meet the accuracy specifications outlined by the FDA, i.e. a mean average error (MAE) <±5 mmHg and standard deviation (SD) <8 mmHg.

Table 2.1. Sensor-Determined Features

Feature	***Description***
P_s	Systolic Blood Pressure
P_d	Diastolic Blood Pressure
P_p	Pulse Pressure
P_m	Mean Arterial Pressure
f	Heart Rate

2.2 Formulas

Listed in **Table 2.2** are three different formulas using the features (noted in **Table 2.1**) to arrive at a reasonable estimate of CO (CO_{EST}): Mean Pressure, the Windkessel model, and the formula developed by Liljestrand and Zander. Each CO_{EST} is to be multiplied by a calibration factor, to obtain CO values. This constant is equivalent to CO / CO_{EST} for each patient and the average of each quotient was regarded the calibration factor.

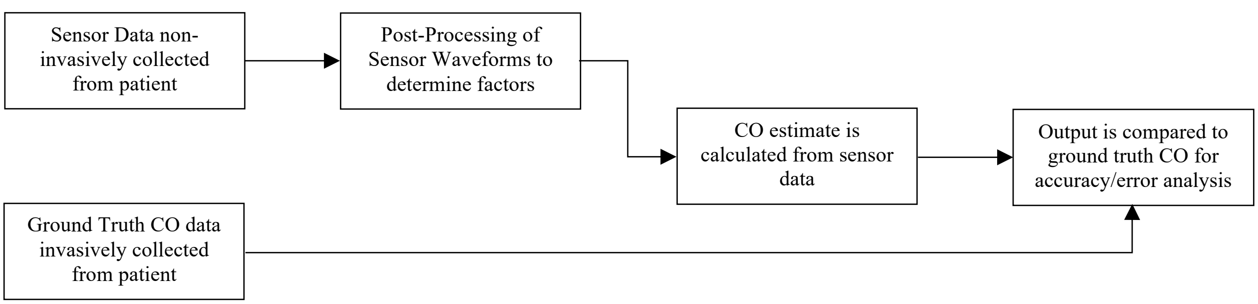
Table 2.2. Formulas and Inputs

Mean Pressure	$P_M \bullet f$
Windkessel	$(P_S - P_D) \bullet f$
Liljestrand & Zander	$\frac{BP_S - BP_D}{BP_S + BP_D} \bullet f$

2.3 Algorithm Evaluation

The files used in the computations consist of one sensor file, containing all the sensor recorded data and estimations for different elements over approximately 8 heartbeats, as well as a corresponding ground truth file used for comparison, containing (invasively) measured data recorded simultaneously and containing values for the corresponding elements. A Python script is used to read in these files, identify the different factors, and calculate the Cardiac Output product using the formulas [Table 2.2].

Figure 2.3. Block diagram of process. Input is live-processed sensor data, from which CO_{EST} is calculated and the product compared to ground truth CO for further analysis.



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Reference Publications

"A Signal Abnormality Index for Arterial Blood Pressure Waveforms" *CinC,* Computing in Cardiology. Accessed 28 Nov. 2019.
[http://www.cinc.org/Proceedings/2006/pdf/0013.pdf]

"Estimating cardiac output from blood pressure and heart rate: the Liljestrand & Zander formula" *NCBI,* US National Library of Medicine — National Institutes of Health. Accessed 11 Jan. 2020.
[https://www.ncbi.nlm.nih.gov/pubmed/25996703]