Cardiac Output Measurements Using NonInvasive Photoacoustic Measurements of Indicator Dilution Signals

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Introduction: Cardiac output (CO)[1] is an important established physiological parameter that enables physicians to optimize fluid and drug interventions in hemodynamically unstable, critically ill patients, in order to improve patient outcomes. Conventional technologies for measuring cardiac output involve using indicator dilution (ID) techniques[2] and require highly invasive pulmonary or femoral arterial catheterization. There is an increasing need for noninvasive devices[3] for assessing hemodynamic status in critically ill patients.

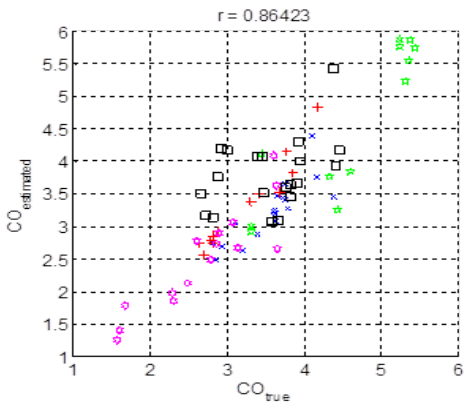
In this abstract, we describe a noninvasive cardiac output measurement technique afforded by the emerging noninvasive photoacoustic technology[4]. In this technique, a small bolus of room temperature isotonic saline is injected quickly into the central circulation of a patient as an indicator, which induces a transient hemodilution effect. A photoacoustic sensor equipped with a single flat ultrasound sensor is placed downstream over a tissue bed with a superficial artery. The sensor noninvasively measures the hemodilution effect from the artery and its nearby vein as the indicator travels across the sensor site. As the indicator is washed out of the circulation, a hemodilution (indicator dilution) curve is noninvasively obtained, and then used to derive hemodynamic parameters, such as cardiac output.

Methods: With AUCC approval, 5 swine with weights ranging from 24.7 to 28.8 Kg were used to demonstrate the feasibility of this new technology. Each swine was anesthetized and intubated with an appropriately sized ETT. The spleen was removed. A 9F double lumen central venous catheter (CVC) was placed in the Internal Jugular Vein (IJV) and advanced to the superior vena cava, and a 5F single lumen PiCCO thermodilution catheter was placed in a femoral artery. 15 ml room temperature saline was then injected through the CVC to verify that an ID curve could be measured by the PiCCO system. The PiCCO thermo-dilution CO measurements were used as the reference. The swine remained anesthetized and ventilated during the experiments. Incision times, closure times, and durations of operative interventions were recorded.

After the animal was prepared, photoacoustic CO experiments were performed to measure the cardiac output of the animal. During the experiments, CO was manipulated by creating a series of "hemorrhagic shocks"[5] by gradually removing blood through the CVC, thereby decreasing the mean arterial blood pressure by 10 mm Hg over a period of 2-5 min in each step. After each reduction of blood pressure, a stabilization period was allowed, for the animal's CO to reach a

steady state. The steady state was assumed when the continuous CO measured with the PiCCO reference becomes stable. CO measurements were performed before the initial CO manipulation and at each steady state. At each steady state, three boluses of 15 cc isotonic saline were injected sequentially at ~1 minute intervals through the CVC, and the CO of the animal was simultaneously measured by the reference PiCCO thermo-dilution technique and the photoacoustic CO system. The photoacoustic CO measurements were obtained with empirical regression analysis with PiCCO thermo-dilution measurements as the references.

Results: The figures below show results for photoacoustic CO estimates from the pool of 5 swine with leave-one-out analysis. The correlation with r^2 of 0.746 between the photoacoustic CO estimates and the PiCCO system over a range of CO from 1 – 6 l/min has been demonstrated as shown in Fig. 1. Figure 2 is the Bland-Altman analysis demonstrating a bias of -0.05 L/min and precision of 0.50 L/min.



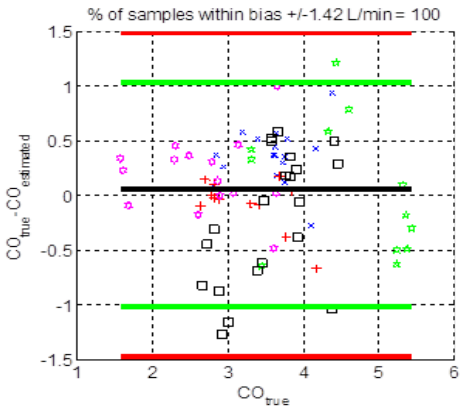


Figure 1. PA CO estimates vs. Reference Device. Figure 2. Bland-Altman Plot, PA CO vs. Reference Device

Conclusion: We verified with *in vivo* study on pig hemorrhagic shock model that noninvasive measurements of an indicator dilution curve with a simple photoacoustic sensor allow successful cardiac output estimation with accuracy comparable with that of an established reference.[6] The present technology does not require differentiating the indicator dilution signals from an artery or a vein. This breakthrough overcomes a major obstacle in the clinical translation of the photoacoustic indicator dilution technology.

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