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Cardiac Output Monitoring by Long Time Interval Analysis of a Radial Arterial Blood Pressure Waveform with Correction for Arterial Compliance Changes using Pulse Transit Time

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***Abstract*—We previously developed a technique for estimating relative cardiac output (CO) change by long time interval analysis of a radial arterial blood pressure waveform. This technique analyzes the slow, beat-to-beat changes in the waveform to circumvent the confounding wave reflections but assumes constant arterial compliance (AC). Here, we sought to correct the CO estimates of the technique for potential AC changes using pulse transit time – a conveniently measured index of AC. For proof-of-concept, we compared the original and corrected techniques using invasive swine hemodynamic data. The corrected technique reduced the overall calibrated CO estimation error by 18% relative to the original technique.**

I. Introduction

A potential approach for achieving continuous and minimally invasive cardiac output (CO) monitoring in surgery and intensive care patients is by mathematical analysis of an arterial blood pressure (ABP) waveform obtained with a radial artery catheter that is already in place. A number of such "pulse contour analysis" techniques have, in fact, been proposed [1]. Generally speaking, while these techniques have been shown to work reasonably well during relatively steady conditions, they have been shown to be inaccurate during the crucial periods of hemodynamic instability (i.e., widely varying CO and/or ABP) [2].

We now believe that two challenges must be overcome for pulse contour analysis to be able to provide accurate estimates of relative CO change during instability. First and foremost, arterial wave reflections, which shape the radial ABP waveform, must be taken into account. Yet, most pulse contour analysis techniques (e.g., pulse pressure (PP) times heart rate (HR)) actually ignore the confounding wave reflections [1]. Secondly, changes in total arterial compliance (AC), which can also alter the radial ABP waveform morphology, must be compensated for in the analysis. While many pulse contour analysis techniques have sought to do so, current ones employ empirical curves relating in vitro AC to ABP [3, 4] and consequently can be prone to error due to any vasomotor tone induced AC changes in addition to inter-subject variability.

We previously developed a technique for estimating relative CO change by long time interval analysis of a radial (or other peripheral) ABP waveform [1]. The idea of the technique is to circumvent the confounding wave reflections by analyzing the slow, beat-to-beat variations in the waveform wherein such phenomena are minimal. Up to now, the main assumption of the technique has been that AC is constant. While we have shown that this assumption can be reasonable in several conditions [1, 5, 6], its validity becomes less tenable with increasing changes in ABP and possibly other conditions of interest.

In this study, we sought to correct the CO estimates of our long time interval analysis technique for potential AC changes using pulse transit time (PTT) – a conveniently measured index of AC. To demonstrate proof-of-concept, we compared the corrected and original techniques based on invasive hemodynamic data from swine.

II. Methods

A. Original and Corrected Techniques

The original long time interval analysis technique is shown in Fig. 1. First, a cardiac contractions signal (x(t)) is constructed from the radial ABP waveform (y(t)) by forming an impulse train in which the impulses are located at the waveform feet and are scaled by the ensuing PPs. Then, a parameterized impulse response (h(t)) is identified, which when convolved with x(t), best fits y(t) in the least squares sense. Next, the Windkessel time constant (τ), which is equal to total peripheral resistance (TPR) times AC, is determined by fitting an exponential to the tail end of h(t) once the faster wave reflections have vanished. (In theory, reliable determination of τ is attained by accurate coupling of the beat-to-beat variations in x(t) to y(t).). Finally, proportional CO is computed by dividing mean ABP (MAP) with τ. Thus, the 1/AC scale factor is assumed to be constant for each subject. (See [1] for full details.)

To correct this technique for possible AC changes, simultaneous measurements of PTT are utilized. According to the well-known Bramwell-Hill equation, PTT is related to AC as follows:

$$PTT = \sqrt{\frac{\rho l}{A} AC},$$

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where ρ is the density of blood, l is the arterial length, and A is the arterial cross-sectional area. Note that since the aorta is the main contributor to AC, PTT here is specifically obtained through the aorta. Thus, the original technique may be corrected for any AC change precisely as follows:

$$CO \propto PTT^2 \frac{MAP}{\tau}.$$

Note that the scale factor now becomes ρl/A. Of these three parameters, only A is expected to be able to change in a subject. However, A has been shown to change much less than AC [7]. Thus, the corrected technique may provide an improved estimate of proportional CO in a subject, particularly during hemodynamic instability.

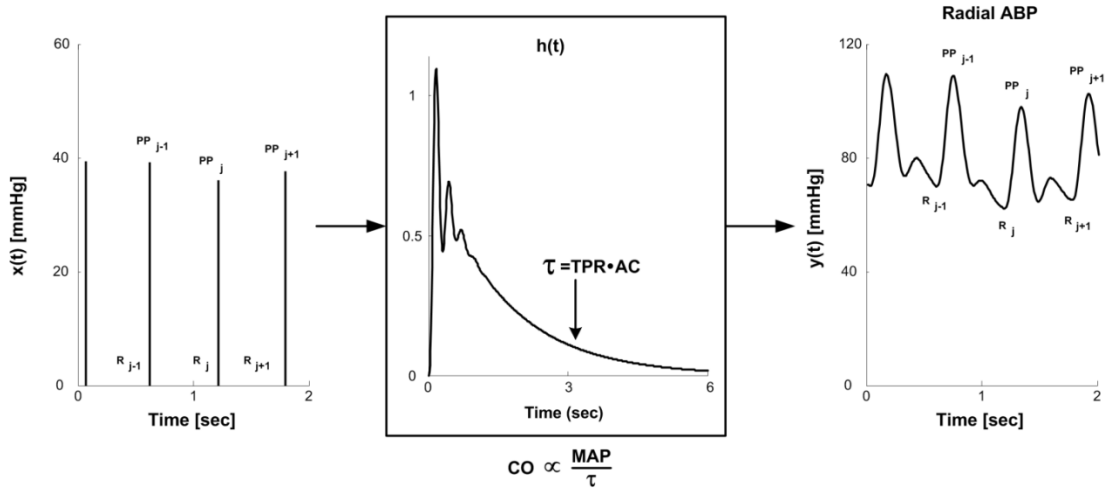

Fig. 1. Original long time interval analysis technique for estimating relative cardiac output (CO) change from a radial arterial blood pressure (ABP) waveform.

B. Technique Evaluation

Both techniques were evaluated using previously collected hemodynamic data [1]. These data included invasive radial and femoral ABP waveforms and aortic flow probe CO from five swine during various drug and volume interventions. MAP/τ was estimated from six-minute segments of the radial ABP waveforms. PTT was measured from the corresponding segments of the aortic flow and femoral ABP waveforms as the average foot-to-foot time delay between these waveforms. The proportional CO estimates of each technique were then scaled to have the same mean value as the aortic flow probe CO for each animal. The root-mean-square of the relative errors between the calibrated CO estimates of each technique and the reference measurements was then computed over all the animals.

III. Results

Fig. 2 shows the results from one animal in which the calibrated CO estimates of each technique are plotted against the reference CO measurements. The corrected technique noticeably reduced the overall scatter about the identity line in the plots. The root-mean-squared-errors over all the animals were 15.7% for the original technique and 12.9% for the corrected technique.

IV. Discussion

In summary, we employed PTT measurements in an attempt to correct the relative CO change estimates of our long time interval radial ABP waveform analysis technique for any AC change. We tested this corrected technique using previously collected data from swine during various drug and volume interventions. Our results showed that the technique was able to reduce the calibrated CO estimation error by 18% relative to the uncorrected technique.

Our available data included only invasive PTT measurements. Thus, the results here demonstrate proof-of-concept. In practice, PTT could be measured non-invasively using, for example, arterial tonometry or pulse oximetry. Further, the average standard deviation of MAP over all the animals was ~15 mmHg. We suspect that the corrected technique will afford greater improvements in CO estimation accuracy during more severe changes to MAP and other modes of hemodynamic instability. Future testing to address both of these issues would be worthwhile.

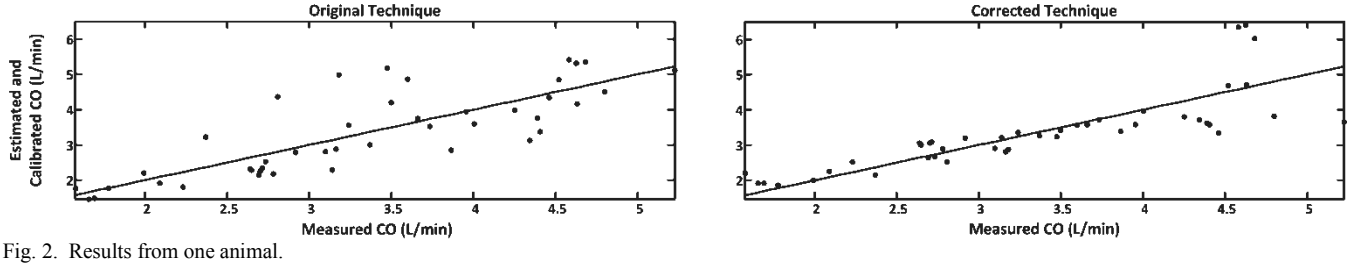

Fig. 2. Results from one animal.

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