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Monitoring Cardiac Output and Left Atrial Pressure by Analysis of the Right Ventricular Pressure Waveform Based on Missing Output Identification

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Abstract—**A proven implantable device is now available for long-term ambulatory monitoring of the right ventricular pressure (RVP) waveform of congestive heart failure patients. However, cardiac output (CO) and left atrial pressure (LAP) are far more useful for assessing cardiac function and managing volume status. We developed a new technique to monitor both CO and LAP by analysis of the RVP waveform based on missing output identification. We initially evaluated the technique against gold standard reference CO and LAP measurements from two dogs during common hemodynamic interventions. We report overall CO and LAP errors of 13.3% and 1.9 mmHg, respectively. With further successful testing, the technique may potentially be employed with an established implantable device for chronic monitoring of vital hemodynamic variables.**

I. Introduction

LONG-TERM ambulatory hemodynamic monitoring with an implantable device has recently been proposed for the growing number of congestive heart failure patients in order to permit optimal day-to-day care, reduce hospital admissions, and eliminate repeated central catheterizations. To this end, an implantable device similar to a conventional single lead pacemaker has been built and validated for ongoing measurement of the right ventricular pressure (RVP) waveform from patients [1-3]. Although RVP itself provides pertinent clinical information, cardiac output (CO) and left atrial pressure (LAP) are far more useful for assessing cardiac function and managing volume status. If these two central hemodynamic variables could be estimated from the RVP waveform, then the benefits of long-term ambulatory hemodynamic monitoring may be fully and conveniently attained with an established device. However, while a number of arterial pressure waveform analysis techniques have been developed to estimate central hemodynamic variables (see, e.g., [4, 5] and references therein), few such *ventricular* pressure waveform analysis techniques have been proposed.

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In this study, we developed a new technique to jointly monitor CO and LAP by analysis of the RVP waveform based on missing output identification. We then initially evaluated the technique against gold standard, but highly invasive, aortic flow probe CO and LAP catheter measurements from a pair of dogs during common hemodynamic interventions.

II. The Technique

We recently introduced techniques based on system identification to monitor CO from a peripheral artery pressure waveform [4, 6] and CO and LAP from the pulmonary artery pressure (PAP) waveform [5]. The basic idea of the system identification paradigm is to analyze the beat-to-beat variations in the waveform wherein simple Windkessel behavior dominates over confounding wave reflections and inertial effects [7]. Our technique for monitoring CO and LAP from the RVP waveform directly arises from the PAP waveform analysis technique by capitalizing on the fact that RVP is nearly equal to PAP during the ejection intervals in absence of pulmonic valve disease.

Fig. 1 illustrates our most recent system identification technique. The technique is applied to 6-min segments of the RVP waveform as follows.

First, the ejection intervals of the RVP waveform segment (y(t)) are detected to yield a partial PAP waveform segment missing diastolic intervals. Specifically, the ejection interval for each beat (j) is identified from the time of the maximal positive derivative (t_{MPD}) to shortly after the time of systolic pressure. Note that the identification of the start of each ejection interval is based on previous studies showing that pulmonary artery diastolic pressure may be well estimated from the value of RVP at t_{MPD} ("ePAD") [8-10].

Second, a cardiac contractions signal (x(t)) is constructed from the ejection intervals of y(t) by forming an impulse train in which each impulse is located at t_{MPD} of each beat and has an area equal to the ensuing pulse pressure (PP). PP here is approximated as the systolic pressure minus $y(t_{MPD})$ (i.e., ePAD).

Third, an impulse response (h(t)) and an additive constant term are identified so as to best couple x(t) to only the ejection intervals of y(t) in the least squares sense (i.e., missing output identification). The estimated constant term represents average LAP, and the estimated h(t) represents the PAP-LAP response to a single cardiac contraction. Since the ejection intervals of y(t) contain limited information (i.e., only high frequencies), h(t) and average LAP are estimated with the following low order output error structure with constant term:

$$y(t) = \underbrace{(b_1 e^{-t/a_1} + b_2 e^{-t/a_2}\cos(a_3 t) + b_3 e^{-t/a_2}\sin(a_3 t))\, u(t)}_{h(t)}, \\ \otimes x(t) + LAP + n(t)$$

where $\{a_k, b_k\}$ are unknown parameters, u(t) is the unit step function, $\otimes$ is the convolution operation, and n(t) is the unmeasured residual error [11]. The unknown parameters including the constant term LAP are estimated from x(t) and y(t) via least squares minimization of n(t) over the ejection intervals. This optimization is specifically achieved through a numerical search over the nonlinear parameters $\{a_k\}$ and closed-form estimation of the linear parameters, $\{b_k\}$ and LAP, for each $\{a_k\}$.

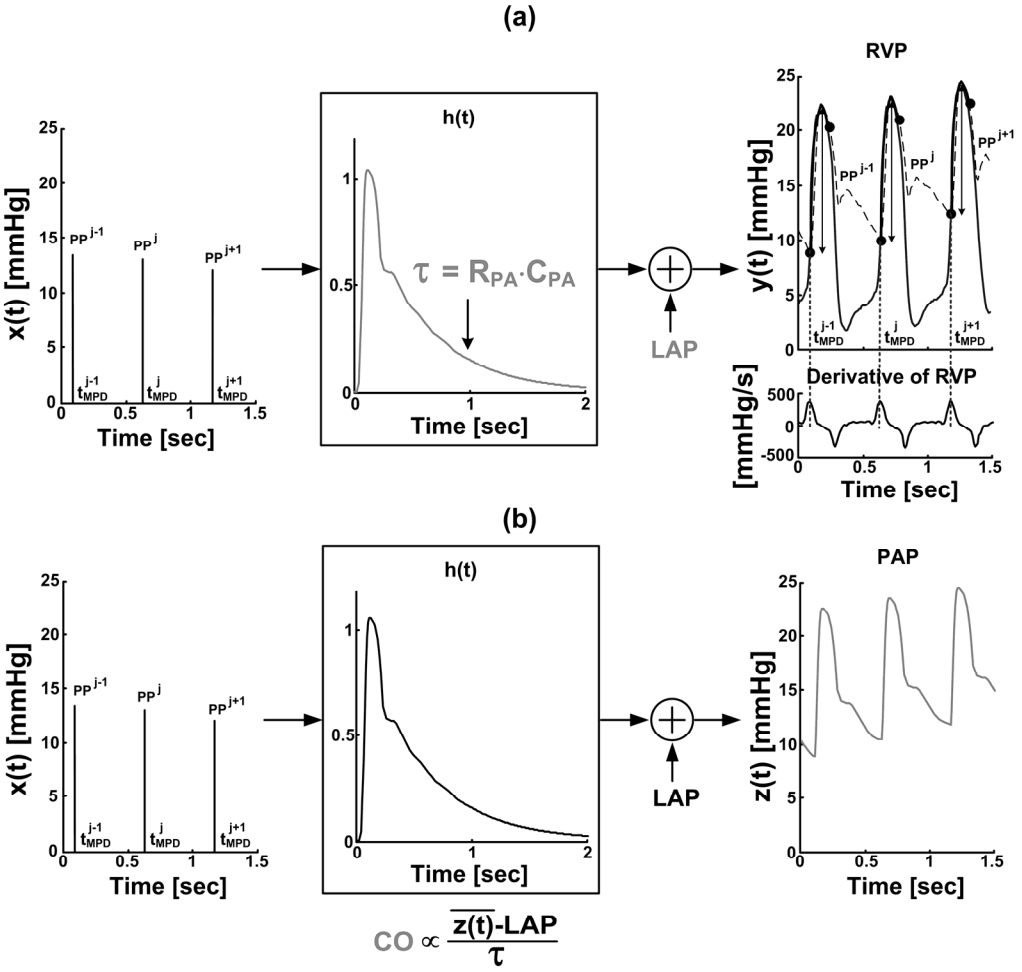

Fig. 1. New technique for monitoring cardiac output (CO) and left atrial pressure (LAP) by analysis of the right ventricular pressure (RVP) waveform based on missing output identification. (a) First, the ejection interval of the RVP waveform (y(t)) is detected for each beat (j) from the time of the maximal positive derivative (t_{MPD}) to shortly after the systolic pressure so as to produce a partial PAP waveform. Second, a cardiac contractions signal (x(t)) is constructed by forming a train of impulses located at t_{MPD} of each beat and scaled by the ensuing pulse pressure (PP). Third, average LAP and the impulse response (h(t)) are identified so as to optimally couple x(t) to y(t) only over the ejection intervals (i.e., missing output identification). Fourth, the Windkessel time constant (τ), which is equal to the product of the pulmonary arterial resistance (R_{PA}) and compliance (C_{PA}), is determined by fitting an exponential to the tail end of h(t) (i.e., the single contraction PAP-LAP response) once the faster wave reflections and inertial effects vanish. (b) Fifth, a full PAP waveform (z(t)) is constructed from average LAP, h(t), and x(t) to establish mean PAP. Finally, assuming constant C_{PA}, proportional CO is computed similar to invoking Ohm's law. Gray indicates calculated quantities.

Fourth, an exponential is fitted to the tail end of h(t) once the faster wave reflections and inertial effects have dissipated to determine the Windkessel time constant (τ) of the pulmonary arterial tree, which is equal to the product of the total pulmonary arterial resistance (R_{PA}) and the lumped pulmonary arterial compliance (C_{PA}). In principle, faithful determination of τ as well as average LAP is achieved by virtue of accurately coupling x(t) to the beat-to-beat variations in the ejection intervals of y(t).

Fifth, the entire PAP waveform segment including its diastolic intervals (z(t)) is constructed by adding average LAP to the convolution between x(t) and h(t). Mean PAP is then computed by time averaging the constructed waveform.

Finally, assuming that C_{PA} is relatively constant, proportional CO is computed by subtracting average LAP from mean PAP and dividing this difference by τ. In this way, the relative change in CO may be monitored. To account for any marked changes in C_{PA} that may occur over

the course of years or when mean PAP changes excessively (see [5] and references therein), the proportional CO could be intermittently calibrated with, for example, ultrasound.

III. Methods

Experiments were performed in two normal adult dogs (10-25 kg) under a protocol approved by the MSU All-University Committee on Animal Use and Care. Each dog was studied on two days under general anesthesia. On the first day, using aseptic techniques, an ultrasonic flow probe (Transonic Systems, Ithaca, NY) was placed around the ascending aorta for reference CO, and a tygon catheter (Norton, Akron, OH) was inserted through the left atrial appendage for reference LAP. The dog was allowed 10-14 days for recovery from the open-chest surgery. Then, on the second day, using fluoroscopic guidance, micromanometer-tipped catheters (Millar Instruments, Houston, TX) were placed in the right ventricle for the RVP waveform for analysis as well as in the main pulmonary artery for the PAP waveform. Surface electrodes were also placed for ECGs. All of the cardiovascular measurements were then recorded during a baseline period and a subset of the following interventions: various infusions of dobutamine, esmolol, phenylephrine, nitroglycerin, and volume.

The technique was then applied off-line to the RVP waveforms. The resulting proportional CO and absolute LAP estimates were quantitatively compared to the gold standard reference measurements as follows. First, the proportional CO estimates were scaled to have the same mean value as the gold standard reference CO in each dog. Then, the root-mean-squared-error (RMSE) of the calibrated CO estimates (in percent) and absolute LAP estimates (in mmHg) were computed. For comparison, the LAP RMSE of ePAD was also computed.

IV. Results

The Table provides a quantitative summary of the results of evaluating the new RVP waveform analysis technique against gold standard reference CO and LAP measurements from the two dogs. This table specifically shows that the technique achieved an overall calibrated CO RMSE of 13.3% and an overall LAP RMSE of 1.9 mmHg over a range of hemodynamic conditions. Fig. 2 provides a visual summary of these results in which the once calibrated CO and absolute LAP estimates from each dog are plotted against their corresponding gold standard reference measurements. For comparison, the overall LAP RMSE of ePAD was 4.8 mmHg.

TABLE
HEMODYNAMIC RANGE AND QUANTITATIVE SUMMARY OF THE EVALUATION RESULTS OF THE TECHNIIQUE OF FIG. 1.

ANIMAL	CO [L/min]	LAP [mmHg]	HR [BPM]	CO RMSE [%]	LAP RMSE [mmHg]
1	0.9-2.4	6.6-16.4	101-139	16.4	2.3
2	3.1-6.0	4.5-11.2	129-148	11.7	1.7
TOTAL	0.9-6.0	4.5-16.4	101-148	13.3	1.9

CO is cardiac output; LAP, left atrial pressure; HR, heart rate; and RMSE, root-mean-squared-error.

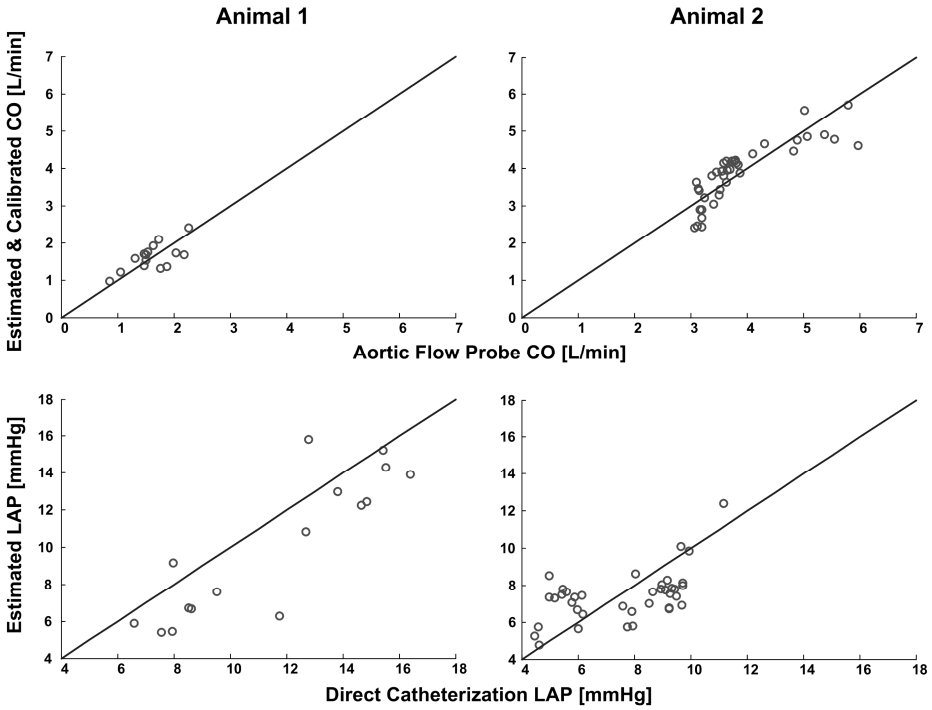

Fig. 2. Visual illustration of the evaluation results of the technique of Fig. 1.

V. Discussion

In summary, we have developed a new technique for monitoring CO and LAP by analysis of the RVP waveform based on missing output identification. We performed experiments in two dogs in order to initially evaluate the technique with respect to gold standard reference measurements. Visually, our results generally indicate good agreement between the once calibrated CO and absolute LAP estimates and the reference measurements. Quantitatively, our results show that the error in the LAP estimates is about 2.5 times smaller than the only other available RVP waveform analysis technique for monitoring LAP. Further, the CO and LAP errors are very similar to those obtained by applying our previous system identification technique to the PAP waveforms (results not shown). With future successful testing, the technique may be utilized for chronic hemodynamic monitoring of congestive heart failure patients with an established implanted RVP measurement device. Moreover, the technique may potentially be employed for continuous hemodynamic monitoring of critically ill patients by way of a right ventricular catheterization instead of the conventional pulmonary artery catheterization, which carries greater risk.

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