A MODEL FOR NON-INVASIVE ESTIMATION OF CARDIOVASCULAR PARAMETERS: CLINICAL VALIDATION

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ABSTRACT

A non-invasive approach has been developed for estimation of hemodynamic parameters in the assessment of human cardiovascular (CV) health from the pressure pulse measured in the radial artery. The computational model consists of a distributed model of the human CV system [1] that, coupled with a parameter estimation scheme, establishes a multi-dimensional relationship between the arterial pressure and flow velocity traces, and the critical clinically useful parameters that determine CV health. Clinical studies conducted on 5 volunteer patients to validate the model have revealed average errors of 30.7% for Systemic Vascular Resistance (SVR) and 19.9% for Cardiac Output (CO) along with good reconstructions of the input pressure profile [2].

INTRODUCTION

Parameters such as Cardiac Output (CO) and Systemic Vascular Resistance (SVR) provide key information regarding the state of cardiovascular (CV) health; hence they are critical for the management of patients with CV dysfunction. As current measurement methods are typically invasive they are not routinely made. If these parameters could be determined non-invasively, it could prove invaluable for patient monitoring in settings such as the OR, wards or even at home.

To address this issue, a model-based method has been developed to allow estimation of certain critical parameters of the CV system from non-invasive measurements. A computational model of the CV system based on one-dimensional equations of motion in a geometrically accurate distributed arterial system was developed to describe blood flow in human arterial networks [1]. The model allows for the study of the relationship between hemodynamic variables usually obtained invasively, such as left ventricular contractility (E_{LV}), end diastolic volume (EDV), SVR and CO, and the morphology of arterial pressure and flow waveforms at various arterial locations. Coupled with a system identification algorithm, the model allows for estimation of these parameters from the shape of measurable Radial Arterial (RA) pressure tracings. Using computer-generated test data, this method provided estimates of within 10% for E_{LV} and EDV, and 3% for SVR [1]. In this work, we report initial results from validation studies in a clinical setting.

METHODS

Clinical Validation

Since many of the parameters of interest are routinely measured during heart surgery, validation studies were carried out on patients undergoing Coronary Artery Bypass Grafting (CABG) at the Massachusetts General Hospital (MGH). As the arterial model assumes a normal arterial geometry and function, patients with aortic aneurysms, prior history of peripheral bypass grafting, amputation, hemodialysis arterial-venous fistulas and any degree of conduction delay were excluded from the study. All studies were performed on volunteers in accordance with a protocol approved by the Human Research Committee (Institutional Review Board) of MGH.

Measurements of CO (via the thermodilution (TD) method) and the electrocardiogram (EKG), radial arterial (RA), pulmonary arterial (PA) and central venous pressure (CVP) waveforms of 5 patients were obtained 4 times during surgery: pre-induction, post induction, post bypass and when the chest was closed. Real time recordings of the hemodynamic data were stored on a Mac Power Book G3 laptop installed with LabView 5.0 software and connected to the OR data distribution center via BNC cables and an NI CA-1000 Data Acquisition (DAQ) system. Whenever possible, CO measurements were averaged over two to three readings.

In addition, transesophageal echocardiographic (TEE) images of the long-axis (LAX) and short-axis (SAX) views of the Left Ventricle and Aortic Valve, respectively, were also digitally recorded on optical disks. After the patient's heart rate (HR), wavespeed and RA pressure waveform were entered into the code, the estimated parameters and the reconstructed waveform were compared against the corresponding measured quantities.

Calculations

A representative cycle of the RA pressure waveform is selected from the 60s recording, and the following variables are calculated:

$$SVR = \frac{P_{mean} - CVP}{CO} \quad (1)$$

where P_{mean} = mean Radial Arterial Pressure, and both P_{mean} and CVP are averaged over the particular cycle.

Wavespeed is calculated using the length of arterial segment from the base of the aorta to the distal end of RA over the corresponding

travel time, taken as the beginning of the QRS complex on the EKG to the initial upstroke on the RA waveform with the Pre-Ejection Period (PEP) subtracted. The PEP signifies the delay in transmission of the pulse to actual ejection of blood from the heart [3] and, though small (~100ms), is non-trivial and greatly affects calculated wavespeed. PEP may be determined in two ways: 1) from echo images (by timing the frames between the QRS complex and when the aortic valve first opens) and 2) by formulae proposed by Weissler [4]. Both methods are used, the results of which will be discussed in the next section. Finally, the percentage errors were calculated between the estimated and measured absolute values of the parameters.

RESULTS

Sixteen data sets were obtained from the 5 patients analyzed. Four runs were not used since their HR's were lower than the minimum value used in producing the parameter estimation library. Overall, the average absolute SVR and CO % errors stand at 30.7% and 19.9%, respectively. From Bland Altman [5] analyses (Fig. 1), the bias and limits of agreement for SVR are 156.43 and (1018, -705) dynes-s/cm5, whilst for CO, they are –0.3 and (1.94, -2.54) L/min.

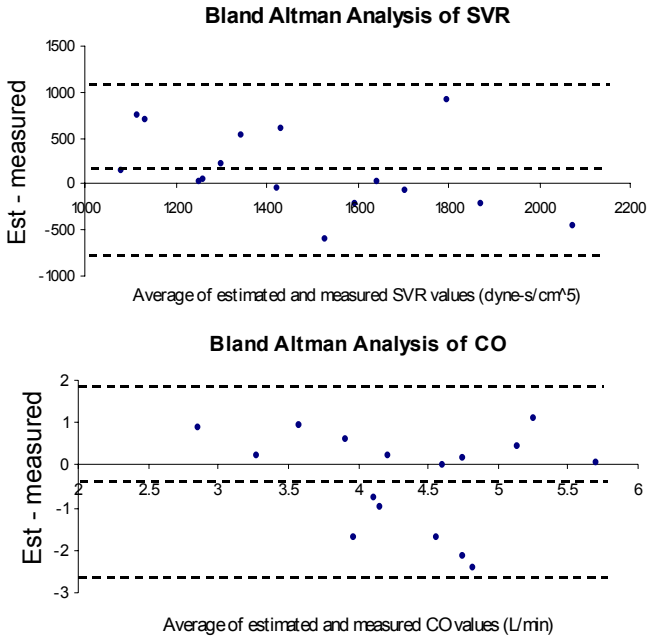

Fig 1: Bland Altman analysis of SVR and CO

Unfortunately, this analysis is based on the assumption of a linear relationship between errors and measurements, and studies have shown that CO measurements have errors that show proportionality to the magnitude of the cardiac output itself. To take into account the proportionality effect, Critchley's [6] error-gram method was also used to analyze the data. Assuming a TD error of 20%, this method revealed a combined error of ±37% and ±28.3% (or 1.42 L/min) for SVR and CO, respectively.

DISCUSSION

Keeping in mind the experimental error for the TD CO measurement method (between 10-20%) [7], based on the guidelines recommended by both precision statistics tests, the present model was found to be able to produce acceptable estimates for CO but not SVR. In an inter-patient analysis, better quantitative results were observed from patients with normal left ventricular function (or EF) with no observable flow disturbance due to valvular dysfunctions. This was expected as our computational model assumes normal valve function.

In terms of qualitative analysis, the reconstructed pressure profiles generally fit well with the measured inputs, matching the basic morphology, amplitude, temporal duration and other characteristic features of the curves. A representative curve fit is shown in Fig. 2.

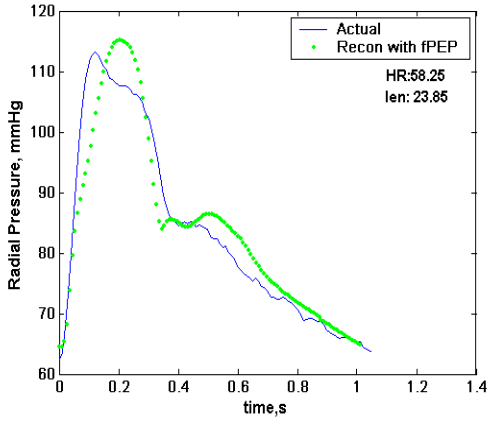

Fig. 2: Representative curve fit

Better curve fits are obtained when the PEP is calculated by formula though this did not translate into better parameter estimates. By virtue of being patient specific, the echo PEP was expected to yield better results, but the formulaic PEP proved better, perhaps because it is statistically determined from 211 normal individuals [4]. No clear trend was also observed from inter-procedural comparisons.

Several improvements might be introduced to reduce the observed error. The assumption of a constant CVP value (5.0 mmHg) used in the model needs to be reevaluated as higher SVR and CO% errors were seen with higher CVP values. Despite accounting for only ~10% of P_{mean}, CVP exerts an important effect on other parameters. The parameter estimation routine might also halt prematurely at a local minimum, instead of the global minimum when matching input and output features. Perhaps different features or feature combinations may be used to better optimize the match, e.g. the slope of the diastolic pressure profile, which is thought to better reflect SVR. The limitations of the code must be realized though, in striking a balance between precision and accuracy and computational efficiency. Clinically, the inherent error in the TD method and the compromised state of patients undergoing cardiac surgery greatly affect the results. Therefore, more trials and further analysis are necessary to fully evaluate and utilize the model.

CONCLUSIONS

A non-invasive CV model has been developed for estimation of key hemodynamic parameters. Clinical tests show good reproductions of RA pressure profiles, and acceptable estimates of CO (assuming 20% TD error). Further work is underway to optimize the cardiovascular model, and to improve the accuracy of the parameter estimation technique.

REFERENCES

1. Xiao X et al. ASME-BED Vol. 50: 67-68, 2001. ASME Press, NY.
2. Tan, JS. 2003 Master's Thesis, Massachusetts Inst. of Technology.
3. Berne RM, Levy MN. Physiology. 4th ed., 1998. Mosby Inc.
4. Weissler, AM. Noninvasive Cardiology, Grune & Stratton, NY.
5. Bland JM, Altman DG. The Lancet 1986; 1:307-310.
6. Critchley LAH, Critchley JAJH. J. Clin. Monit. 1999; 15:85-91.
7. Stetz CW et al. Am Rev Respirat Dis 1982; 126:1001-1004.