Time varying elastance estimation in an 8 chamber cardiovascular system model

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Introduction: Time-varying elastance curves are a common means of characterizing left and right ventricle function [1]. However, assessing elastance requires a highly invasive vena-cava occlusion maneuver and left and right ventricle pressure/volume waveforms, which are not typically available in an intensive care unit (ICU) and may raise ethical issues in regular use. A validated, lumped-parameter 8 chamber cardiovascular system (CVS) model is used to evaluate a time-varying elastance estimate at the bedside using standard clinical measurements.

Objectives: To assess time-varying elastance at the bedside for the left and right ventricles using available ICU data, and prove the concept on a porcine model of pulmonary embolism.

Methods: Five pigs had pulmonary embolism (PE) induced via injection of blood clots over 4 hours, developing full PE in stages from a healthy state. At each state several data sets were taken (46 in total over 5 pigs), measuring aortic and pulmonary artery pressure waveforms ($P_{ao}(t)$, $P_{pa}(t)$), left and right ventricular volume and pressure waveforms (Vlv(t), Vrv(t), Plv(t), Prv(t)).

At each cardiac state in inducing PE, the time-varying elastances are estimated as Elv=Plv/Vlv and Erv=Prv/Vrv. These values are correlated to readily measured quantities (Pao and GEDV). These correlations are used to approximate time-varying elastances Erv* and Elv* for use in a clinically validated 8-chamber CVS model. Note these approximations are load dependent and thus change with cardiac state.

A five-fold cross validation was used to validate the model. A time-varying elastance is generated from data from 4 pigs and used to simulate the fifth pig. Simulated PV loops are compared to the originally measured PV loops to validate the approach.

Results: $P_{ao}(t)$ and Elv were highly correlated over the 46 data sets (R=0.81 to R=0.99). $P_{ao}(t)$ and Elv, GEDV and Erv are also well correlated (R=0.73 to R=0.98). Using the five-fold cross validation, the median errors (of 46) in the correlation-based estimates (Elv*, Erv*) of Elv and Erv to the measured ratios are 1.32% and 2.5% [90^{th} percentile: 3.67%, 9.43%]. Simulated left and right ventricle PV loops have median errors of 8.3% and 7.0% [90^{th} percentile: 11.5%, 13.1%] from measured values.

Conclusions: Left and right ventricle elastance curves can be estimated using typical ICU measurements of aortic pressure and global end-diastolic volume at any time or given cardiac state. With the addition of SV and pulmonary artery pressure measurements, this CVS model can accurately predict ventricular PV loops and thus ventricular function at the bedside. These results are the basis of an ongoing clinical trial in human subjects.

Reference:

[1] Segers P, Steendijk P, Stergiopulos, N, Westerhof N (2001). Predicting systolic and diastolic aortic blood pressure and stroke volume in the intact sheep. Journal of Biomechanics 34: 45-50.