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Original Article

Accuracy of a Simulation Algorithm for Modelling LV Contractility, Diastolic Capacitance, and Energetics Using Data Available From Common Hemodynamic Monitors and Echocardiography

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Objective: To test the hypothesis that a simulation algorithm populated with data readily available from hemodynamic monitors and echocardiography can accurately model cardiac contractility, diastolic capacitance, and energetics.
Design: Bland-Altman analysis of paired data sets.
Setting: University laboratory.
Participants: Archived data previously recorded from 7 anesthetized swine.
Measurements and Main Results: Left ventricular pressure and volume (LVV) data that had been continuously recorded over a range of inotropic conditions were used as reference data. One investigator performed conventional analysis of measured pressure/volume loops during preload reduction to derive reference values for end-systolic elastance (Ees—a measure of contractility), the predicted LVV at an end-diastolic pressure of 30 mmHg (V_{30}—an index of diastolic capacitance and chamber dilation), and pressure-volume area (PVA—a correlate of myocardial oxygen consumption). Other investigators blinded to these results entered pressure, cardiac output, and ejection fraction measurements into a simulator that predicts Ees, V_{30}, and PVA. Analysis of simulated data was performed before and after correction of the estimated LVV at which pressure would be 0 mmHg (V_0), which was initially fixed in the model. Before V_0 correction, accuracy and precision of Ees, V_{30}, and PVA tended to fall outside predefined limits for method interchangeability, but utility for qualitative assessment of acute changes was evident. After V_0 correction, the accuracy and precision of simulated data were within the defined limits for method interchangeability.
Conclusions: These data support the potential for clinical utility of simulation models populated with data readily available at the bedside to characterize left ventricular mechanical performance and energetics.

Key Words: left ventricle; simulation; inotropy; capacitance; energetics

GIVEN THE EXTENT of hemodynamic monitoring and wide spectrum of pathophysiology commonly encountered in cardiac surgery operating rooms, these areas have long represented a rich environment for teaching cardiovascular physiology. The rapid expansion of catheter-based procedures for structural heart disease has now provided an added dimension by allowing access to real-time measurements of pressure in the left ventricle (LVP), often in conjunction with cardiac imaging by transthoracic or

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transesophageal echocardiography. While clinicians are accustomed to using systemic arterial systolic pressure and intermittent pulmonary capillary wedge pressure as surrogates for left ventricular (LV) peak and end-diastolic pressures, respectively, the ability to continuously observe LVP in the context of simultaneous echocardiographic representation of LV dimension or volume (LVV), and often right heart pressures as well, enhances qualitative assessment of how effectively the heart empties and fills.

Integrating data from multiple sources into a format for *quantitative* assessment of cardiac performance in the operating room is more challenging. Despite widespread appreciation of the basic concepts behind using the continuous relationship between LVP and LVV to quantify systolic and diastolic function—virtually every modern textbook of cardiovascular physiology includes a figure depicting "pressure/volume (P/V) loops"—clinical application in the perioperative environment has remained relatively uncommon. Major hurdles have been, and largely remain: (a) the technical limitations associated with acquiring adequate source data; and (b) access to analytic modules that easily summarize continuous data into finite variables that quantify specific aspects of cardiac function.

Recently, a simulation platform became readily available that allows for combining data displayed on hemodynamic monitors with echocardiographic measurements to derive quantifiable summary indices of LV contractility, diastolic compliance, and energetics.[1] Based upon predictive models of end-systolic and end-diastolic P/V relationships (ESPVR and EDPVR, respectively),[2] the simulator is embedded within a commercially available digital textbook of cardiovascular physiology.[1] However, whether the simulation models can effectively track changes in cardiac physiology over a range of functional states is unknown. In order to test the hypothesis that the simulation algorithm can accurately model LV function when populated with data available in cardiac operating rooms, 3 steps were applied. First, a reference data set was constructed from archived hemodynamic recordings obtained in a previous study involving inotropic manipulation in swine.[3] These source data included continuous P/V measurements during variation in preload, thus facilitating calculation of gold standard reference values for: (a) LV end-systolic elastance (Ees), a *load-independent measure of contractility*; (b) the predicted LV volume at an end-diastolic pressure of 30 mmHg (V_{30}), *an index of diastolic capacitance*; and (c) LV pressure-volume area (PVA), the sum of potential and external work expenditure that *correlates with myocardial oxygen consumption*.[4,5] Second, measurements of pressure, cardiac output, and LV ejection fraction derived from the source data were entered into the simulator, and predicted values for Ees, V_{30}, and PVA were compared to directly measured reference data. Finally, additional procedures were applied to correct for an assumption in the simulation that may affect accuracy during wide variation in cardiac performance.

Methods

Archived recordings of LVP and LVV sampled at 200 Hz and stored to disc were used as source data for the study. Data had been obtained under a previously described protocol approved by the Institutional Animal Care and Use Committee of Memorial Sloan Kettering Cancer Center from 7 anesthetized swine.[3] That study was primarily focused upon the effect of equipotent pressor doses of dobutamine, dopamine, and phenylephrine on perfusion of myocutaneous flaps; information related to measurement of LV P/V relationships in these animals has not been previously reported. All procedures had been carried out in accordance with the NIH Guide for the Care and Use of Laboratory Animals. Briefly, during pentobarbital anesthesia and mechanical ventilation (tidal volume 12 cc/kg, 5 cmH_2O positive end-expiratory pressure), a 5-Fr conductance/micromanometer catheter had been advanced from a femoral artery into the LV using the transition from ascending aortic to LV pressure as a guide. Once in the LV, appropriate catheter position had been assessed by visual inspection of 5 individual volume segments measured by the catheter and used to quantify total volume.[6] Parallel conductance had been determined by injection of hypertonic saline, and stroke volume was cross-calibrated to thermodilution measurements obtained via pulmonary artery catheter. Acute variations in cardiac preload had been produced by filling a balloon catheter in the inferior vena cava with 30 cc saline. For each animal, LVP and LVV had been continuously recorded at baseline and then following the addition of 1% halothane to alter inotropic state. Halothane administration was then continued during intermittent infusion of dobutamine (2.5-5.0 μg/kg/min), dopamine (3.0-6.0 μg/kg/min), and phenylephrine (1.5-3.0 μg/kg/min). For each treatment, data were obtained with the ventilator off but maintenance of positive end-expiratory pressure over a ~12-second interval that included cardiac cycles before and during caval occlusion.

Reference Data

Analysis of directly measured P/V data obtained during preload variation was performed with the LabChart PV module (ADInstruments, New South Wales, Australia). A minimum of 5 beats occurring immediately after caval occlusion were included in the analysis; given the depth of anesthesia and rapid, transient response, no additional steps were taken to mitigate autonomic reflexes. The LabChart PV module defines end-systole as the point of maximal P/V ratio for each beat (ie, when active tension is maintained but the heart is relatively empty) and uses the linear decline of this point as preload decreases to define Ees as the slope and V_0 as the x-axis (volume) intercept (ie, the volume remaining if pressure were to decline to 0 mmHg) (Fig 1).[5,7] At the same time, the nonlinear EDPVR is defined using the equation: end-diastolic pressure = β * exp(α *end-diastolic volume), with β and α determined from characteristics of each loop sequence using V_0 as the 0 pressure asymptote (Fig 1). From the EDPVR, V_{30} was calculated as an index of LV capacitance or how dilated the heart will be with an end-diastolic pressure of 30 mmHg (Fig 1).[5] Based upon stroke work, the ESPVR, and the EDPVR, the LabChart module estimates myocardial

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