Assessment of myocardial performance with ventricular pressure-volume relations: clinical applications in cardiac surgery

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The assessment of myocardial performance in patients with cardiomyopathy is of vital importance in cardiology and cardiac surgery, especially considering the significant increase in the number of patients treated for congestive heart failure. Left ventricular pressure-volume analysis is a method, which can assess accurately myocardial contractility, separating the systolic and diastolic function at different preload and afterload conditions. This technique can be used for determination of the efficacy of a therapeutic pharmaceutical or surgical intervention, for instance the assessment of ventricular function after coronary revascularization. A few studies using the conductance catheter for the analysis of ventricular pressure-volume relations in the field of cardiac surgery have been published. In our center we started to use this technique to analyze cardiac surgical procedures, like mitral valve reconstruction, aortic valve replacement, myocardial revascularization, left ventricular assist, and surgical left ventricular remodeling. This information will be used to develop a therapeutic strategy, which may optimize surgical indications and improve the peri- and postoperative treatment and the efficacy of that surgical technique. In this short review the possible clinical use in cardiac surgery and the methodology of the pressure-volume loops have been described. Three clinical cases are presented to demonstrate functional information related to the surgical treatment of congestive heart failure patients.

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Introduction

Assessment of myocardial performance, function and contractility is a critically important task in the evaluation of many patients with known or suspected heart disease. Ventricular performance is related to the pumping function of the ventricle, as reflected in cardiac output, which is the expression of the heart s prime function to deliver sufficient oxygenated blood to meet the metabolic requirements of the tissues. Determination of cardiac output does provide a useful measure of the pumping ability of the heart. However, cardiac output is critically dependent on preload, afterload and heart rate in addition to myocardial contractility. Ventricular function relates cardiac output or cardiac work to preload, afterload and pressure or ventricular wall stress. Myocardial contractility, also called inotropic state, refers to a fundamental property of cardiac muscle, which in the final analysis, reflects the level of activation of cross-bridge formation and the rapidity of cross-bridge cycling.

The measurement of the myocardial contractile state is of vital importance in daily clinical practice especially in the field of cardiac surgery. Recent years have witnessed significant improvements in cardiac surgical techniques and in methods of myocardial preservation, which have allowed cardiac surgeons to treat an increasing number of high-risk patients with heart failure. The search for the ideal assessment of myocardial contractility is therefore paramount in cardiac surgery and might provide a method for a better patient selection and surgical strategy planning. It may improve intraoperative and postoperative management with a significant impact on clinical results. This review will outline possible clinical applications of ventricular pressure-volume relations as a powerful method for assessing ventricular performance in cardiac surgery.

The cardiac cycle and the ventricular pressure-volume curves

The earliest attempts to separate loading conditions from contractility in assessing ventricular performance used the Frank-Starling relation. This is the intrinsic ability of the heart to adapt to different preloads; the more the heart is filled during diastole, the greater will be the strength of cardiac contraction and therefore the amount of blood pumped into the aorta.

The transformation of myocardial function to left ventricular pump function can be understood by presenting the cardiac cycle in the pressure-volume plane (Fig. 1). The cardiac cycle consists of a filling phase (diastole) followed by isovolemic contraction (systole), the ejection phase (systole), and finally the isovolemic relaxation phase (diastole). With the opening of the mitral valve, left ventricular filling begins. Ventricular end-diastole is followed by a brief period of isovolemic ventricular contraction, the maximum rate of pressure change (peak dP/dt) occurring just before the onset of ejection. The onset of inward motion of the ventricular wall commences as blood is ejected into the aorta. The peak ejection rate falls near the middle of the ejection phase. Wall thickness increases during shortening, becoming maximal at the end of ejection. Thereafter the contraction reaches its peak at end-systole, the myocardial fibers begin to relax, and when left ventricular pressure falls below aortic pressure, the aortic valves close, and cardiac ejection stops. Then the isovolemic relaxation starts and ventricular pressure decreases rapidly, subsequently the left ventricular pressure-volume curve is completed.

Over the past 20 years, pressure-volume relation analysis has evolved as a powerful method to understand left ventricular performance. The measurement of multiple pressure-volume loops over a loading range can provide valuable insight into left ventricular contractility and is able to separate chamber function into primary systolic, diastolic and vascular loading factors[1]. While initially studied in isolated hearts, this approach has been applied to intact animals[2,3] and more recently to man[4-8]. This has been facilitated by the development of a method to continuously measure intraventricular volume, the conductance catheter volume technique[4]. With this technique, a multielectrode catheter is passed across the aortic valve, and the tip is positioned in the apex of the left ventricle. An electric field is generated in the left ventricle between the distal electrodes positioned at the tip of the catheter and proximal electrodes just above the aortic valve. Sensing electrodes that are evenly distributed along the catheter are used to measure potentials produced by the current. The system enables the measurement of five separate cross-sectional volumes, perpendicular to the long heart axis. Dedicated software calculates the total volume of the chamber in real time. Pressure changes within the left ventricle, measured with a solid-state pressure sensor, are combined with the volume data to construct real-time pressure-volume loops over successive cardiac cycles. By applying hemodynamic interventions, such as a transient caval vein occlusion, both systolic and diastolic pressure-volume relations may be acquired with relative ease.

Systolic function

As introduced by Suga and Sagawa[9], the upper left corner of variably loaded pressure-volume loops defines the left ventricular end-systolic pressure-volume relation (ESPVR). In the physiological range, this relation can be approximated as a straight line and can therefore be described with a slope called end-systolic elastance (E_{es}) and volume axis intercept (V_0) (Fig. 1). E_{es} has dimensions of pressure/volume and therefore represents the end-systolic elastance of the left ventricle and indicates

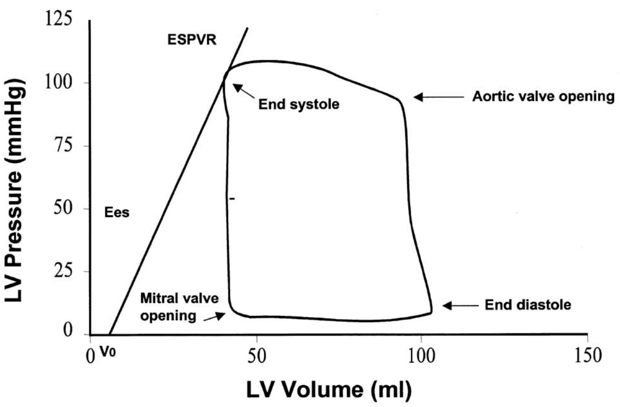

Figure 1. *A left ventricular (LV) pressure-volume loop of one cardiac cycle. The LV end-systolic pressure-volume relation (ESPVR) is used to describe LV systolic performance and is approximated by a straight line. The line can be described in terms of its slope (end-systolic elastance - E_{es}) and volume axis intercept (V_0).*

how sensitive the ejection is for changes in afterload. With enhanced contractility, E_{es} becomes steeper. The volume axis intercept (V_0) of the ESPVR has been referred to as the dead volume of the ventricle, which corresponds to the volume at which the left ventricle would generate no pressure.

The position of the ESPVR on the volume axis at the operating pressure indicates the extent of contraction. A leftward shift means that the same end-systolic pressure is reached at a smaller end-diastolic volume than during control, or stated another way, a higher end-systolic pressure is generated at the same end-diastolic volume; this represents an increase in contractile performance. In contrast, a rightward shift of the ESPVR represents a decrease in contractility[10].

The ESPVR has the advantages of defining a boundary of systolic performance, providing insight into the interrelation between changes in chamber loading and systolic pressure, and of easily relating to vascular load and measurements of chamber energetics. Its disadvantage is that it demonstrates some load dependency, although the precise magnitude of this in humans remains unclear[11]. To calculate the slope E_{es} a preload change, mostly performed by caval vein occlusion, should be performed. This method often results in insufficient decreases particularly in patients with congestive heart failure[6]. However, recently Senzaki et al.[12] have developed a method to calculate the ESPVR slope and its positions from sing le cardiac cycles without having to change loading conditions.

Diastolic function

While a major focus of clinical applications of pressure-volume relations has been on systolic performance, diastolic chamber properties can be equally well defined. The passive characteristics of the left ventricle can be described as the end-diastolic pressure-volume relation[13-16], outlined by the same multiple and variably preloaded beats used to derive systolic function measures. Optimally, the passive left ventricular diastolic pressure-volume relation should be constructed from points that are obtained after relaxation is complete and at a slow filling rate, so that viscous effects are not present[15,16]. The slope or the curvature of the end-diastolic pressure-volume relation is related to the chamber stiffness.

Like the ESPVR, the diastolic pressure-volume relationship is intrinsically related to preload and can be determined by obtaining multiple pressure-volume loops by inferior caval vein occlusion. This procedure markedly unloads the right heart prior to left ventricular preload reduction, thereby reducing right-left ventricular interaction. Furthermore, using only the end-diastolic points from multiple pressure-volume relations enables end-diastolic pressure-volume relations to be determined over a volume range with little to no influence from delayed relaxation or viscoelastic properties.

Clinical applications

The pressure-volume framework has proven to be a fertile area of research, and has significantly helped to broaden our understanding of cardiac mechanisms and hemodynamics. With the development of new techniques such as the multielectrode conductance catheter, providing on-line continuous left ventricular volumes, and methods of rapid reversible load alteration such as inferior caval vein occlusion, clinical applications are finally coming within reach. Pressure-volume loops provide clinicians with visual and parametric information regarding the performance of the right and left ventricle as a pump and help to identify the pathophysiology of cardiac dysfunction and the extent of impairment[17-20]. The technique enables cardiologists to determine the success of different therapeutic interventions such as pacing-optimization strategy in several types of heart disease, quantifying the effects of positive and negative inotropic drugs, quantifying systolic and diastolic performance of the ventricles after heart failure treatment with ACE-inhibition, and the response to vasodilators in patients with various forms of heart disease[21-24]. Conductance catheters have been used in the catheterization laboratory during coronary angioplasty in order to determine the influence of coronary occlusion on g lobal left ventricular function[25]. The ultimate efficacy of reperfusion techniques, whether thrombolytic agents or angioplasty, often relies on a demonstration of improved pump performance. Therefore characterization of g lobal systolic and diastolic dysfunction with coronary occlusion and reperfusion in man is another fundamental use of pressure-volume relations.

The use of pressure-volume loops in cardiac surgery

Despite the increasing experimental and clinical applications of pressure-volume relations for the assessment of ventricular performance, few studies have been conducted in the field of cardiac surgery[7,26-29]. Some studies have analyzed the changes in systolic and diastolic function after heart surgery using pressure-volume relationships, demonstrating that continuous measurement of left ventricular pressure-volume loops using conductance catheters was a feasible and useful tool to estimate left ventricular performance[6,7,30-33].

We have started to evaluate the efficacy of several surgical strategies in patients with different cardiac pathologies undergoing cardiac surgery. Previous studies in patients with heart failure undergoing cardiomyoplasty, demonstrated the great value of pressure-volume analysis to evaluate left ventricular function improvements after the surgical procedure, and has convinced us to apply the same methodology in other types of cardiac surgical corrections, especially in patients with heart failure[30-32]. The long-term goal of our studies is to develop a treatment strategy for heart failure patients in which innovative diagnostic techniques, surgical procedures and perioperative treatment are integrated. Current applications of the pressure-volume analysis in our institution involve several surgical procedures:

mitral valve repair in patients with severe mitral valve regurgitation;

aortic valve replacement in patients with severe aortic stenosis or incompetence;

coronary artery bypass grafting on the beating heart without the use of cardiopulmonary bypass and cardioplegic arrest;

surgical treatment of atrial fibrillation in patients with end-stage heart failure and/or mitral valve pathologies with the use of atrial epicardial radiofrequency ablation;

use of intraaortic balloon counterpulsation and other left ventricular assist devices;

partial left ventriculectomy and aneurysmectomy.

To monitor the hemodynamics continuously we also use a beat-to-beat cardiac output device, which was developed based on pulse contour algorithms with automated sing le shot thermodilution calibration[34,35]. Routine transesophageal echocardiography is used in each patient. A conductance catheter with a high fidelity pressure sensor is inserted via the right upper pulmonary vein into the left ventricle, and the correct position of the catheter is verified by transesophageal echocardiography. Patients undergoing mitral valve repair using the edge-to-edge technique, aortic valve replacement, beating heart coronary revascularization and ventricular remodeling with aneurysmectomy have been recruited for the initial part of the project.

From ventricular pressure-volume loops, aortic and mitral valve regurgitation can be demonstrated and quantified. Moreover, several systolic and diastolic indices of pump function can be derived instantaneously.

The conductance catheter provides five segmental volume signals from the apex to the base of the left ventricle, which can be analyzed to detect asynchronous or paradoxical wall motions throughout the cardiac cycle (Fig. 2).

The solid-state pressure transducer, mounted on the conductance catheter, gives reliable left ventricular pressures, from which derivations, such as positive and negative peak dP/dt and the time course of left ventricular pressure decay (tau), can be calculated.

By way of summarizing the previous discussion, and to clarify how this approach is used practically, a few clinical examples are provided.

Case 1. A 58-year-old male patient with dilated cardiomyopathy in NYHA functional class IV underwent cardiomyoplasty. In figure 3 left ventricular pressure-vol-

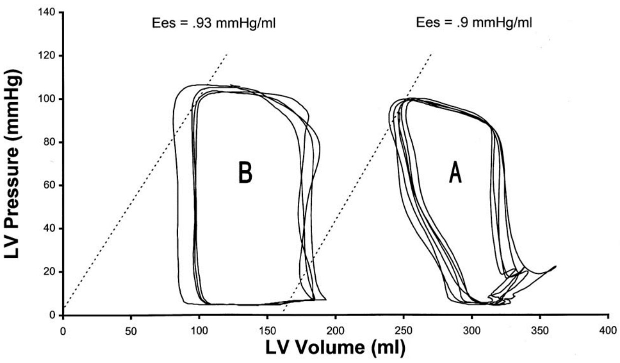

Figure 2. *Left ventricular (LV) segmental volume changes during three successive cardiac cycles from case 1, before* (A) *and after* (B) *cardiomyoplasty. The marked segmental left ventricular asynchrony decreased 6 months after the procedure.*

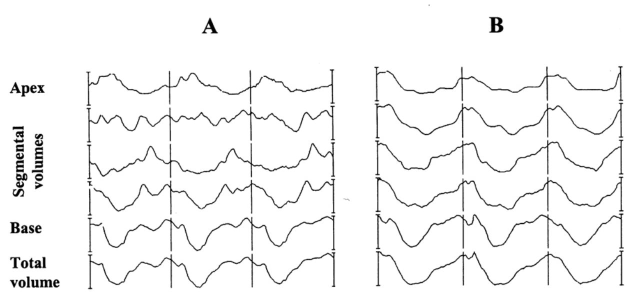

Figure 3. *Pressure-volume loops of a patient (case 1) with dilated cardiomyopathy, before (A) and 6 months after (B) cardiomyoplasty. End-systolic elastance did not change, whereas its position shifted markedly to the left.*

ume loops are presented, which were acquired before and 6 months after cardiomyoplasty. The cardiomyoplasty induced a marked shift of the pressure-volume loops to the left, left ventricular end-diastolic volume decreased by 45%, end-diastolic pressure decreased from 20 to 7 mmHg, and tau decreased from 52.5 to 48 ms. E_{es} as calculated from sing le loops[11] did not change. However, its position shifted to the left indicating an improved contractile state. Figure 2 shows left ventricular asynchrony between 5 segmental volume tracings from the same patient, representing wall motion abnormalities, before and after cardiomyoplasty. Together with the decrease in left ventricular dimensions, an improvement in left ventricular synchrony can be observed. The patient was in NYHA functional class I 6 months after cardiomyoplasty.

Case 2. A 58-year-old male patient with dilated cardiomyopathy in NYHA functional class IV underwent partial left ventriculectomy. In figure 4 left ventricular pressure-volume loops acquired before, immediately after and 5 days after the surgical procedure are shown. Partial left ventriculectomy resulted in an intraoperative left ventricular end-diastolic volume decrease of 50%, while end-diastolic pressure increased during the procedure, which decreased 5 days after surgery.

Case 3. A 70-year-old male patient with coronary artery disease and left ventricular aneurysm underwent aortocoronary bypass and left ventricular aneurysmectomy according to the Dor procedure. In figure 5 pressure-volume loops recorded immediately before and after cardiopulmonary bypass are shown. The recordings were performed during a short period of caval vein occlusion. The aneurysmectomy resulted in a decrease of the end-diastolic volume of 50 ml. The preoperative ESPVR was characterized by an E_{es} of 1.8 mmHg/ml, which increased after cardiopulmonary bypass to 3.2 mmHg/ml, indicating an immediate increase of the contractile state. Ejection fraction increased from 45 to 60%.

Conclusions

Continuous registration of both intraventricular pressure and volume, with or without a preload intervention to obtain systolic and diastolic pressure-volume relations, appears to be a feasible approach for assessing myocardial function during cardiac surgery. Despite the popularity of pressure-volume analysis in animal research, this approach is relatively new to clinical studies. We have provided examples where conductance catheters can be used in heart failure patients undergoing cardiac surgery. It is expected that with further im-

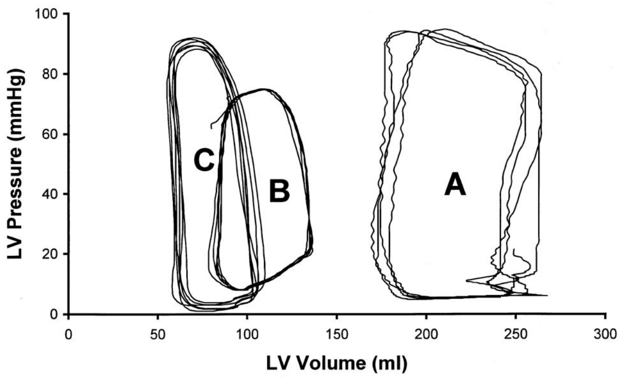

Figure 4. *Pressure-volume loops of a patient (case 2) with dilated cardiomyopathy, before (A), immediately after (B) and 5 days after (C) partial left ventriculectomy. The procedure lead to a marked decrease in left ventricular (LV) dimensions and to a decreased diastolic compliance.*

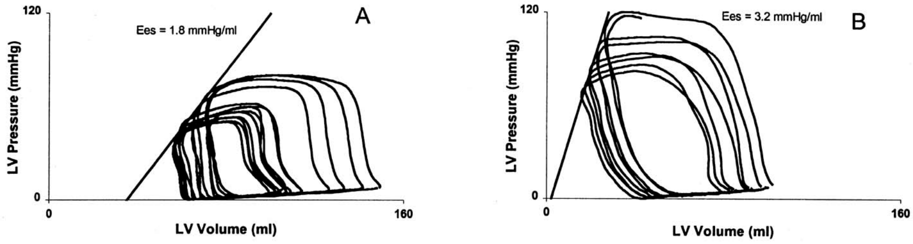

Figure 5. *Pressure-volume loops of a patient undergoing left ventricular (LV) aneurysmectomy recorded during preload reduction before (*A*) and immediately after (*B*) surgery. End-systolic elastance (E_{es}) increased sharply after aneurysmectomy.*

provements, this approach will become more widely accepted as a standard for evaluating human heart function, providing new insights into the mechanisms of heart disease, aiding clinical diagnosis and may therefore become a further step towards a better medical treatment for so many patients.

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