On Measuring the Absolute Ventricular Volumes for the Estimation of End Systolic Pressure-Volume Relation in Rabits

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Abstract. *The paper deals with a new approach to calibrate the measurement of absolute left intraventricular volumes, necessary to compute the elastance curve and End-Systolic Pressure-Volume Relation (ESPVR) on single cardiac cycles. The method is based on using the conductance catheter technique, while injecting known absolute volumes of blood in the isolated left ventricle and has been tested on rabbits. Thus the influence of the parallel conductance does not affect the volume measurement anymore.*

Keywords: End Systolic Pressure-Volume Relation, Elastance, Left Ventricle Volume, Conductance Catheter, Rabbit.

1. Introduction

To characterize left ventricular contractile status more methods and indexes have been developed (1-6). ESPVR is a valuable tool; it designates a maximal elastance (maximal pressure/volume ratio). A traditional way to estimate ESPVR is to alter the heart load and use multiple cardiac cycles (Figure 1). Inducing such a transitional status is time consuming and increases the risk of heart failure. It was assumed the ESPVR stay on a line (see red line in Figure 1, left). Whether this linear relation stands it is still debated, evidence suggesting a nonlinear evolution of ESPVR or, in other words, only local linearity.

Such computations have been largely based on arbitrary mathematical curve fitting of left ventricular pressure data measured during isovolumetric contraction and relaxation of an ejecting beat. Different studies showed the linearity is just an assumption [1], raising questions on the accuracy of the ESPVR thus computed. Attempts have been made to compute the ESPVR on single cardiac cycles using algorithms, not always convergent [7].

We proposed [7] an original algorithm which is always convergent and provides accurate computation of the elastance curve and ESPVR on single cardiac cycles.

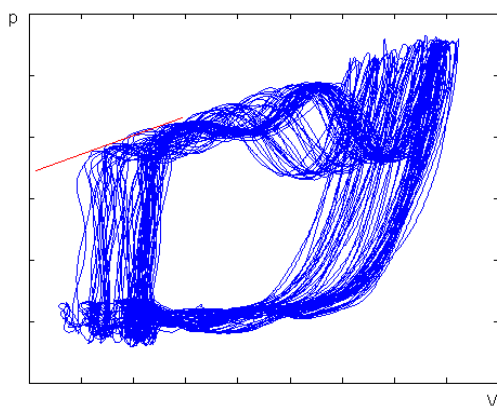One of the problems is to determine absolute ventricular volumes by using the conductance catheter technique, where an estimate of the conductivity of structures surrounding the ventricular blood pool on parallel conductance is required. Usually, the contribution of the parallel conductance ranges from 50 to 70% of the total volume signal [8, 9]. Thus it is important to accurately quantify this volume offset, or to accurately measure the volume. Parallel conductance volume is normally estimated by injection of hypertonic saline, which transiently changes the conductivity of the blood in the ventricle [10] with disadvantages: (i) inappropriate saline loading with multiple

Figure 1. Cardiac cycles during a transition – an approximate ESPVR curve (relative units).

measurements, while being difficult to perform in small animals and (ii) the characteristics of the injectate itself may alter the calculated values [11] and hemodynamics [10]. Our work shows a technique of calibrating the measurement of absolute left intraventricular volumes, alleviating the above mentioned disadvantages of the mentioned methods.

2. Subjects and Methods

We performed preliminary experiments in 6 New Zealand rabbits (2.5 – 4.2 Kg) of either sex, anaesthetized with sodium pentobarbitone (40 mg/Kg, I.V.) supplemented as necessary with IV bolus injections. The descending aorta was cannulated retrogradely through the femoral artery with a Swann-Ganz catheter (Edwards size 4F, Baxter, UK) and the arterial blood pressure was measured by connecting the lumen of the catheter to a pressure transducer (SensoNor 840). The left carotid bifurcation was identified and the tip of a plethysmography catheter with an open central lumen was placed inside the left ventricle by retrograde cannulation of the common carotid artery to allow the simultaneous recording of left ventricular pressure (SensoNor 840) and volume (conductance plethysmography Dias Amado).
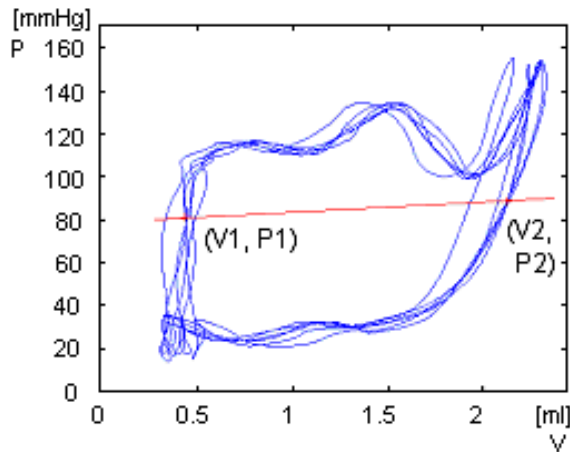

Figure 2. Two points of equal elastance are shown (red crosses) on one of the cardiac cycles, to illustrate the method.
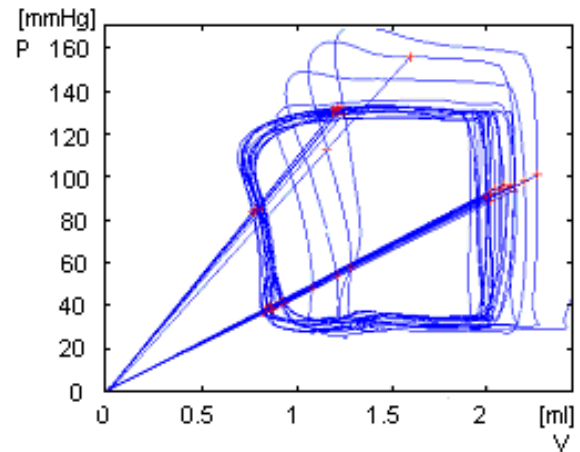
Figure 3. V0 is at the intersection of the equal elastance lines with the V axes (relative units).

The electrocardiogram (ECG) was recorded (Lectromed) from four electrodes applied to the limbs. Pressure, volume and the ECG were recorded. At the end of the experiment the animal was killed with an overdose of anaesthetic and the magnitude of infarction was confirmed in the isolated heart. Estimates derived from the normalized elastance curve are physiologically based and have the potential for noninvasive assessment. To compute the elastance (E) at any instance of the cardiac cycle, the current ventricular pressure (P) and volume (V) are needed together with a residual computational volume (V_0):

$$E(t) = \frac{P}{(V - V0)} \qquad (1)$$

To estimate V_0, our method [7] takes into consideration two conditions of equal elastance, one in the diastolic (V_1, P_1) and the other the systolic phase (V_2, P_2) of the same cardiac cycle (Figure 2). The algorithm computes an initial estimate of V_0 using these states of equal elastance:

$$V_0 = P_2(V_2 - V_1)/(P_2 - P_1) \qquad (2)$$

Iteratively refined, V_0 (Figure 3) allows the computation of the elastance curve on all the current cardiac cycle. ESPVR is built by the points of maximal elastance and corresponds to the instances of end-systolic maximal pressure.
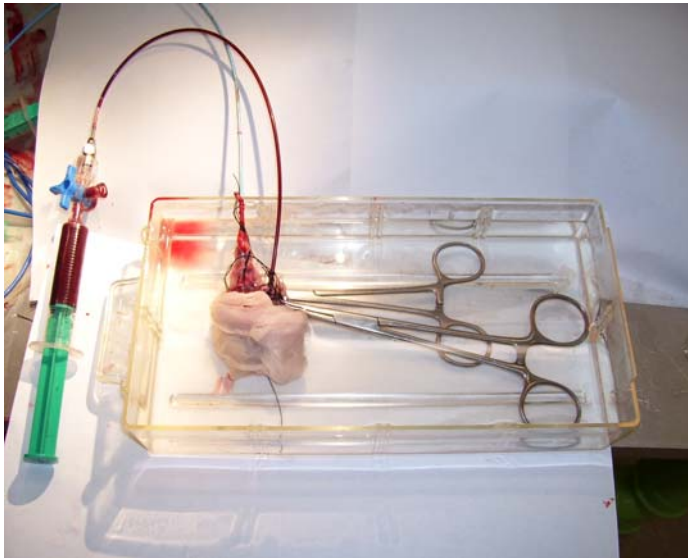

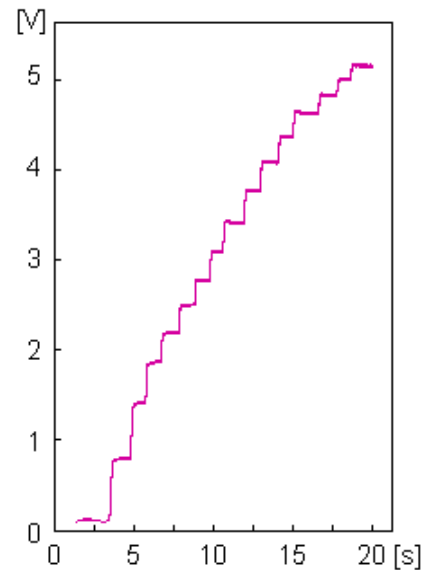**Figure 4.** Isolated heart prepared for volume calibration

Figure 5. Calibration curve – steps of 0.2 ml, starting from 0.

The volume calibration is performed on the isolated heart, progressively injecting (Figure 4) in the left ventricle heparinated blood, in increments of 0.2 ml. Figure 5 shows the calibration curve. The resulting voltage, corresponding to known absolute volumes, generates a function through cubic interpolation, which is subsequently used to read actual real absolute volumes from the previously recorded data.

3. Results

Using this procedure and the method [6] to compute the cardiac elastance in single cardiac cycles, the elastance for an 'average' animal model (rabbit) could be computed, together with important cardiac parameters: Ejection Fraction ($0.4221 \pm .1238$), End Diastolic Volume ($1.4845e\text{-}6 \pm 4.1403e\text{-}7$ m^3), End Systolic Volume ($8.2268e\text{-}7 \pm 1.4823e\text{-}7$ m^3), Emin (dP/dt) ($1.1505e\text{+}10 \pm 4.1974e\text{+}9$ Pa/ m^3), Emax (dP/dt) ($1.1505e\text{+}10 \pm 4.1974e\text{+}9$ Pa/m^3). The averages were taken on 2000 individual cardiac cycles, equally distributed on the animal population the experiments wee performed on.

4. Discussion and conclusions

To ignore V_0 and report the elastance as p/V would be inadequate as there are marked differences in V_0 in cases of infarction or dilated cardiomyopathy i.e. V_0 is sensitive to the pathologic condition of the heart. In situations of high contractility V_0 may have negative values. The similarity between V_0 computed on single cardiac cycles and V_0 computed on multiple cardiac cycles suggests that the evolution of elastance within the physiological loading range can locally predict linear ESPVR. This also supports the idea that nonlinear physiology rather than volume-catheter signal artifacts during Inferior Vena Cava obstruction explains negative values for V0. Thus, the accurate computation of the elastance, based on absolute ventricular volumes and accurate V0, is essential. The algorithm and the calibration method we developed, provide the automatic, dynamic computation of the elastance curve on

single cardiac cycles and therefore of the ESPVR. The algorithm offers an adequate quantitative tool to refine physiological studies on the heart and circulatory system condition. The preliminary results are encouraging us to further refine the work.

References

[1]   Noda T, Cheng CP, DeTombe PP, Little WC. Curvilinearity of LV end-systolic pressure-volume and dP/DTmax – end-diastolic volume relations. Am. *J. Physiology* 265:H910-H917, 1993.

[2]   DeTombe PP, Jones S, Burkhoff D, Hunter WC, Kass DA. Ventricular stroke work and efficiency both remain nearly optimal despite altered vascular loading. *Am. J. Physiol.* 264 (Heart Circ. Physiol. 33) H1817-H1824, 1993.

[3]   Asanoi H, Kameyama T, Ishizaka S, Nozawa T, Inoue H. Energetically Optimal Left Ventricular Pressure for the Failing Human Heart, *Circulation,* Vol.93, No.1, January 1 67-73, 1996

[4]   Burkhoff D, DeTombe PP, Hunter WC, Kass DA. Contractile strength and mechanical efficiency of left ventricle are enhanced by physiological afterload, *Am. J. Physiol.* 260 (Heart Circ. Physiol. 29) H569-H578, 1991.

[5]   Karunanithi MK, Feneley MP. Single-Beat Determination of Preload Recruitable Stroke Work Relationship: Derivation and Evaluation in Conscious Dogs, *Journal of the American College of Cardiology*, Vol.35, No.2:502-512, 2000

[6]   Tarata M., Silva-Carvalho L., Rocha Isabel, Rosario L. A New Approach to Single-Beat Estimation of the Elastance Curve of the Cardiac Muscle, Proceedings of The 1st MEDINF Int. Conference on Medical Informatics & Eng. MEDINF' 2003, October 9 - 11, 2003, Craiova, Romania, Craiova Medicala Journal, ISSN 1454-6876, Vol. 5, Sup. 3, (2003): 218-221.

[7]   Senzaki H, Chen C-H, Kass DA. Single_Beat Estimation of End_Systolic Pressure_Volume Relation in Humans – A New Method With the Potential for Noninvasive Application, *Circulation,* Vol.94, No.10, November 15:2497-2506, 1996.

[8]   Steendijk P, Lardenoye JW, Van Der Velde ET, Sehalij MJ, Baan J. Evaluation of a new transcardiac conductance method for continuous on-line measurement of left ventricular volume. *Crit Care Med* 28: 1599–1606, 2000.

[9]   White, P.A., Brookes, C.I.O., Ravn, H., Hjortdal, V., Chaturvedi, R.R., Redington, A.N. Validation and utility of novel volume reduction technique for determination of parallel conductance. *American Journal of Physiology* - Heart and Circulatory Physiology, Volume 280, Issue 1 49-1, H475-H482, 2001.

[10]   Baan J, Van der Velde ET, Hein G, Debruin HG, Smeenk GJ, Koops J, Van Dijk AD, Temmerman D, Senden J, Buis B. Continuous measurements of left ventricular volume in animals and humans by conductance catheter. *Circulation* 70:812–823, 1984.

[11]   Herrera MC, Olivera JM, and Valentinuzzi ME, Parallel conductance determination in cardiac volumetry using dilution manoeuvres: theoretical analysis and practical implications.*Med Biol Eng Comput* 37:169–174, 1999.