Time Course of Left Ventricular Pressure-Volume Relationship under Various Extents of Aortic Occlusion

Hiroyuki Suga, M.D.

SUMMARY

The author has reported that a variable, e(t)=p(t)/v(t), is approximately unchanged in the areflexive heart of the dog over a wide range of end-diastolic volume of the left ventricle, where p(t) is systolic left intraventricular pressure, v(t) is systolic left intraventricular volume, and t is time from the beginning of systole in each cardiac cycle. e(t) is studied further under various extents of an aortic occlusion, without the change in left intraventricular end-diastolic volume, monitored on left intraventricular end-diastolic pressure of the areflexive heart of the dog.

For actual computation,

\[ e(t) = \frac{p(t)}{(1-\rho)^{-1} \cdot v_s - \int_0^t i(t) \, dt} \]

where p(t) is measured by a straingauge electromanometer, \( \rho \) is residual volume ratio measured by a thermodilution method, \( v_s \) is stroke volume as time-integral of ascending aortic flow velocity \( i(t) \) in a given cardiac cycle, and \( i(t) \) is measured by an electromagnetic flowmeter. End-diastolic volumes of the left ventricle are kept approximately constant by controlling venous return to the heart with a balloon-catheter in the inferior vena cava. The results show that e(t) is approximately unchanged by an ascending aortic occlusion, in spite of the conspicuous changes in \( p(t) \), \( i(t) \) and \( v(t) \) in each dog. Therefore, e(t) is considered to be a steady and characteristic variable of the pumping properties of the areflexive left ventricle.

Additional Indexing Words:
Ventricular compliance    Ventricular elastance    Ventricular distensibility

The author has been investigating the pumping properties of the left ventricle from the viewpoint of time course of pressure-volume relationship of the left ventricle. A new variable has been proposed to describe the relationship as follows:

From the Institute for Medical Electronics, Faculty of Medicine, University of Tokyo, Hongo, Tokyo.

Present Address: Institute for Medical and Dental Engineering, Tokyo Medical and Dental University, Tokyo.

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\[ e(t) = \frac{p(t)}{v(t)}, \]

where \( p(t) \) is systolic left intraventricular pressure, \( v(t) \) is systolic left intraventricular volume, and \( t \) is time from the beginning of systole in a given cardiac cycle. \( e(t) \) is known to have a characteristic and approximately unchanged time course over a wide range of end-diastolic volume of the left ventricle of the vagotomized and stellectomized dog. \(^{1)} \) Besides end-diastolic volume, the loading conditions of the arterial system is an important factor exerting influence on the ventricular pumping. The purpose of the present investigation is to study whether \( e(t) \) is influenced by various extents of an ascending aortic occlusion.

**METHODS**

Seven mongrel dogs (ca. 10 Kg.) were anesthetized with sodium pentobarbital (25 mg./Kg.), and thoracotomized bilaterally in the 3rd intercostal space under positive pressure ventilation. As Fig. 1 shows, an electromagnetic flowmeter probe was placed at the aortic root. A catheter with a thermistor (time constant 50 msec.) at its tip was introduced about 2 cm. peripheral to the aortic valve through the right common carotid artery. Another catheter, with its tip closed and several side holes, was introduced into the left ventricle through the left atrial appendage or the

![Fig. 1. Schmatic diagram of the experiment.](image-url)
This catheter was connected to a three-way cock and used either for measurement of $p(t)$ or for injection of saline for thermodilution. A catheter with a balloon at its tip was introduced into the inferior vena cava in order to control venous return to the heart, hence, end-diastolic volume of the left ventricle. Bilateral vagi were severed in the neck, and stellate ganglia were isolated bilaterally from its branches except their cardiac nerves. The aortic root was mechanically occluded to various extents between the flowmeter probe and the beginning of the brachiocephalic artery. At first, left intraventricular end-diastolic volume was fixed by inflation of the balloon with the end-diastolic pressure monitored, and several trials of thermodilution were performed after cessation of transient changes in $p(t)$ and $i(t)$ in order to know residual volume ratio $\rho$ of the left ventricle, which was used to calculate left intraventricular end-diastolic volume $v(o)$ by use of the Holt’s formula:

$$v(o) = v_s/(1-\rho),$$

where $v_s$ is stroke volume. Therefore,

$$v(t) = v(o) - \int_0^t i(t) \, dt.$$ 

Then the aortic root was occluded to a certain extent, and left intraventricular end-diastolic pressure was made equal to almost the same value before the occlusion with venous return controlled by inflation of the balloon. With the same $v(o)$, several steps of the aortic occlusion were performed in a series, and $p(t)$ and $i(t)$ were recorded on an ink-pen writer at a speed of 125 mm/sec. Experiments were done on several steps of $v(o)$ in every dog. $v(t)$ and $e(t)$ were calculated from every 20 msec. sampled values of $p(t)$ and $i(t)$ tracings.

**Results**

Fig. 2 shows examples of simultaneous tracings of $i(t)$’s, $p(t)$’s and highly amplified $p(t)$’s which show almost unchanged left intraventricular end-diastolic pressures, hence, almost the same end-diastolic volumes $v(o)$’s. Computed $v(o)$ from $i(t)$ without the aortic occlusion and $\rho=0.61$ was 36 ml. in this case, and this $v(o)$ was used as $v(o)$’s from b to e in the figure. As the aortic occlusion was intensified, tracings of $i(t)$ and $p(t)$ were markedly changed as follows: the peak flow velocity decreased, the ejection phase increased with almost unchanged beginning of the phase, the peak systolic intraventricular pressure increased with almost unchanged pressure in the isovolumetric contraction phase but high pressure in the isovolumetric relaxation phase. $\rho$ was increased to a great extent by the aortic occlusion, as in Fig. 2.

Fig. 3 shows a comparison of the time courses of the calculated $e(t)$’s from a to e in increasing order of the aortic occlusion in Fig. 2. In spite of the marked changes in $i(t)$ and $p(t)$, $e(t)$ was approximately unchanged in its time course and magnitude: $e(t)$ was increased in the first $2/3$ of systole of a cardiac cycle, and decreased in the last $1/3$ of systole. Mean of peak time of $e(t)$ was 230 msec. (SD 22 msec., 7 dogs), and in each dog about 7% of mean of peak time of $e(t)$ was the standard deviation SD of the peak time, for example, mean
Fig. 2. Comparison of ascending aortic blood flow velocity $i(t)$, left intraventricular pressure $p(t)$ and left intraventricular end-diastolic pressure (highly amplified $p(t)$) under various extents of the ascending aortic occlusion, with the same end-diastolic volume of the left ventricle. a: without the occlusion; b, c, d and e: with the occlusion in increasing order of its extent.

DISCUSSION

As it was discussed in the previous paper,\textsuperscript{1) the accuracy of calculated $e(t)$ depends to a great extent on that of residual volume ratio $\rho$ of the left ventricle of the peak time was 255 msec. and SD was 16 msec. (N=18, Dog #57). Mean of peak value of $e(t)$ was 7.2 mm.Hg/ml. (SD 1.8 mm.Hg/ml., 7 dogs), and in each dog about 10% of mean of peak value was the standard deviation of the peak value, for example, mean of the peak value was 5.2 mm.Hg/ml. and SD was 0.6 mm.Hg/ml. (N=18, Dog #57).
measured by a thermodilution method. In order to eliminate the variability of ρ, the mean of ρ's from 3 or 4 trials of thermodilution in a given steady conditions of p(t) and i(t) is used for calculation of e(t). The standard deviation of ρ is usually 0.02 without the aortic occlusion, and this amounts to about 5% of v(o) at ρ=0.6. In spite of this variability, it is obvious that p(t), i(t) and v(t) are characteristically changeable depending on the loading conditions of the arterial system, with the same end-diastolic volume of the left ventricle. These characteristic changes have been studied by many investigators, from various standpoints,4),5) but any concept like e(t) has not been discussed there. Measurements of i(t) and p(t) for calculation of e(t) are done after cessation of the transient changes in p(t) and i(t), usually 20 to 30 sec. after each stepwise change in the extent of the aortic occlusion, hence, the intrinsic adaptation of the left ventricle to the increased loading is considered to have been completed.6) But, contribution of this adaptation is not analysed in detail in this study. In spite of the above-mentioned conspicuous changes in the circulatory variables, the time course and the magnitude of e(t) are approximately unchanged by the aortic occlusion.

Considering these results and those in the previous paper,1) it is evident that e(t) is a steady and characteristic variable of the pumping properties of the left ventricle, and that the left ventricular pumping is described by the following equation with e(t) over a wide range of v(o) and the arterial loading conditions:
\[
p(t) = \varepsilon(t) \left\{ \nu(\alpha) - \int_0^t i(t) \, dt \right\},
\]

where \( t \) is time from the beginning of systole in a cardiac cycle when time-integral of \( i(t) \) is set to zero, and \( f \) is the function of the hydraulic impedance of the cardiac load, including the aortic valvular properties.1)

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**References**