

Time Constants for Switching Flow in Left Ventricular Output Impedance

Herman B.K. Boom and Hessel Wijkstra

Biomedical engineering division. Department of electrical engineering. University of Twente
University for technical and social sciences. P.O. Box 217, 7500 AE Enschede, the Netherlands

ABSTRACT

Pressure curves obtained in isolated rabbit hearts after the end of externally imposed constant flow pulses were divided by isovolumic pressure curves at the same volume. An exponential decay to a constant level, generally lower than one, was observed. The time constant equaled that found for switching-on of the flow pulse. The results indicate that flow deactivation can be described as a decrease of ventricular elastance.

INTRODUCTION

Under suitably chosen conditions the output impedance of the left ventricle can be described by a small number of well defined functional components. A slowly ejecting ventricle presents a unique relation between volume and intraventricular pressure [1], giving rise to the concept of elastance, $E(t) = e \cdot f(t)$. Greater, more physiologic flow rates show a pressure component proportional to flow, implying a 'resistance' $R(t) = r \cdot f(t)$, [2].

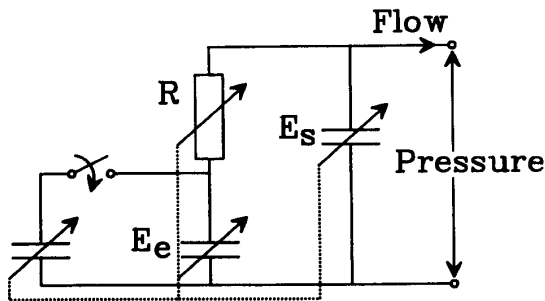


Figure 1. Analog circuit modeling left ventricular output impedance. Voltage is analogous to pressure, charge to volume and current to flow. Elastances E and E_s as well as R vary according to the same time function $f(t) = \frac{E(t)}{e} = \frac{E_s(t)}{e_s} = \frac{R(t)}{r}$. When a constant flow is terminated impaired capability of pressure redevelopment is assumed to be presentable by closing the switch, thus decreasing E stepwise: e becomes e' .

At still faster volume changes a second much stiffer elastance, $E_s(t) = e_s \cdot f(t)$, emerges ($e_s \gg e$) [2]. Thus the substitute analog circuit of Fig. 1 describes ventricular output impedance [3]. Interestingly, the components vary according to the same time function, $f(t)$ (identical to the time course of the isovolumic pressure), suggesting a common active mechanism underlying Fig. 1. The time 'constant' involved in starting a constant flow pulse, as predicted by Fig. 1, i.e. $R/(E+E_s)$, did not change in time. It equaled 10.35 ± 0.25 ms, [2].

Predicting pressure/volume/flow relations for non-constant flow requires a test of the validity of Fig. 1 for increasing and decreasing flow. For increasing flow Fig. 1 was shown valid, at least for switching-on of a flow pulse, [2]. Switching-off the flow pulse showed a more complicated response. We investigated how this response could be represented by an instantaneous change of the circuit in Fig. 1 at the time of the switching-off.

THEORY

Generally isovolumic pressure generated after the end of a constant flow pulse differed from the value predicted by Fig. 1 at the particular volume. We hypothesized that the lower pressure might be represented as the result of closing the switch in Fig. 1, thus ensuing an instantaneously decreased elastance e .

At any time during and before a (constant) flow pulse Fig. 1 predicts pressure to be given by:

$$p^*(s) = \frac{(s + \nu) q_T(s) - Q_E(0)}{(s + \nu_s)} \cdot e_s \quad (1)$$

In eqn. (1), $p^*(s)$ denotes the Laplace representation of ventricular pressure divided by $f(t)$. The reciprocal time constants ('frequencies') ν and ν_s are given by: $\nu = e/r$, $\nu_s = (e + e_s)/r$ where e, e_s and r are defined in Fig. 1. $q_T(s)$ is the Laplace representation of the total volume ($Q_T(t)$) in E plus E_s . $Q_T(t)$ is controlled by experiment. $Q_E(0)$ is the volume in E at some arbitrary $t=0$.

If at $t=0$ a (constant) flow has stopped $Q_T(t)$ stays constant: $q_T(s) = Q_T(0)/s$. Since it is assumed that at $t > 0$ e may be lower than at $t < 0$, e is replaced by e' . Isovolumic pressure measured at volume $Q_T(0)$ is given by:

$$p^*(\text{iso}) = e_s \cdot (\nu/\nu_s) \cdot Q_T(0) \quad (2)$$

Also this pressure has been divided by $f(t)$. In (2) $e_s \cdot (\nu/\nu_s) = e_s \cdot e/(e+e_s)$ is the in parallel connection of e and e_s . Equation (1) divided by (2) yields:

$$\frac{p^*(s)}{p^*(iso)} = \frac{\nu_s \cdot (s+\nu')}{\nu \cdot s(s+\nu'_s)} - \frac{Q_e(0)/Q_T(0)}{s + \nu'_s} \quad (3)$$

Both terms on the right hand side of (3) represent an exponential decay with time constant $1/\nu'_s$. However, only the first has a non zero asymptote which is at:

$$\frac{\nu' \nu'_s}{\nu \nu'_s} = \frac{e'(e+e_s)}{e(e'+e_s)} \approx \frac{e'}{e} \quad (4)$$

This ratio would be one if $e=e'$.

METHODS

Constant flow pulses experimentally imposed on isolated rabbit ventricles (external pumping) [2] verified eqn. (3). From $t=0$ onwards an exponential was fitted to the pressure ratio values including that part of the plateau judged horizontal by the eye.

This procedure was repeated for 908 beats. Amplitude, time of onset and duration of flow pulse were experimental variables.

RESULTS

The experimental counterpart of (3) is shown in Fig. 2.

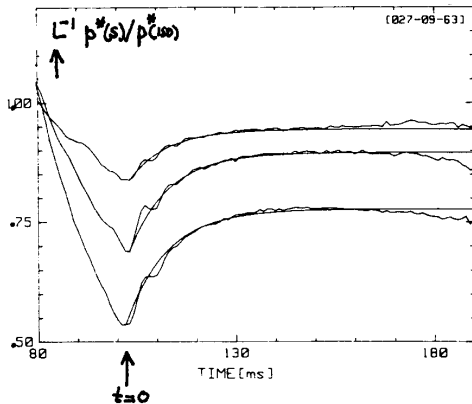


Figure 2. Response of $p^*(s)/p^*(iso)$ to termination of constant flow (at arrow). Flow values are 5, 10 and 15 ml/s. Flow duration is 33 ms.

Constant flow is switched off at $t=0$ (arrow). During the flow pulse the ratio declines according to Fig. 1, [4]. Following the flow pulse an exponential regeneration occurs to a constant plateau level. Generally this plateau extends beyond the time corresponding to physiologic end systole. Mean error of exponential fit was 0.007 ± 0.003 (SD). Mean time constant (to be compared with $1/\nu'_s$) was 10.44

± 0.09 (SEM). No relation between the time constant and the above experimental variables could be detected. These data indicate that after flow termination only one time constant is effective thus supporting the hypothesis that the switch in Fig. 1 is at the right position. The difference between the switching-off and switching-on (see introduction) time constants is not significant. According to the theory the time constants are related by:

$$\nu'_s/\nu_s = (e'+e_s)/(e+e_s) \text{ which approaches 1 since } e_s \gg e.$$

DISCUSSION

That the ventricle does not restore its full activity after ejection (flow deactivation) has been attributed to a decreased elastance by others on theoretical grounds [5]. Sliding filament theory, [6] suggests that flow deactivation is essentially an impaired capability to reactivate cross-bridges decoupled by filament sliding. The rate constant for reactivation as reflected in the switching-off time constant would not be impaired. The time independent time constant seems at variance with results by Hunter et al. [7], who found deactivation to increase markedly towards the end of the systole. Our results were found by dividing isovolumic pressure values at the same volumes, thus eliminating the complication that the shape of the isovolumic pressure curve is volume dependent, especially towards the end of the systole

REFERENCES

- [1] H. Suga, K. Sagawa. *Circulation Research*, 35, 1974, 117-125.
- [2] S.R. Vaartjes, H.B.K. Boom. *Circulation Research*, 60, 1987, 12pp.
- [3] P. Schiereck, H.B.K. Boom. *Pflügers Archiv*, 374, 1978, 135.
- [4] H.B.K. Boom, H. Wijkstra. *Proc. IXth Ann. Conf. BME-IEEE*, Boston USA, 1987, 161.
- [5] J. Lefevre, J. Melbin, A. Tavenier, F. Messemackers, Y. Ijkmans, H. Pouleur, A. Charlier, A. Noordergraaf. *38th ACEMB*, 1985.
- [6] A.F. Huxley. *Progr. Biophys. Biophys. Chem.* 7, 1957, 255.
- [7] W.C. Hunter, J. Janicki, K. Weber, A. Noordergraaf. *Circ. Res.* 52, 1983, 319.