Revisiting the Evaluation of the Performance of Fluid-Filled Catheters

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Abstract: A new method to evaluate the performance of fluid-filled catheters and to reconstruct input pressure waves is described. The method we advocate assumes that pressure waves recorded through such a catheter and through a tip-catheter (Sentron) taken as reference for the input pressure, belong to a underdamped, second order, linear system. The parameters of the model are estimated through an identification procedure that, in addition, allows to evaluate how the model fits the data. Reproducibility of the results is examined. The opportunity of this method with respect to the "pop-test" method and the "frequency response" method is briefly discussed.

INTRODUCTION

Fluid-filled catheter-pressure transducer systems are frequently used to measure blood pressure waves. To a good approximation, such systems can be described by a second order linear differential equation which express the relationship between pressure recorded through the system and true pressure at the open end of the catheter. Most often, the undamped natural frequency ω_n and the damping ratio ζ are estimated from an input step response obtained by performing a "pop-test" [1,2]. In the "pop-test", the system is subjected to a constant hydrostatic pressure that is suddenly released to a zero level or inversely. In both cases, the recorded pressure oscillates around a steady state value. The parameters ω_n and ζ are estimated from the frequency and the magnitudes of the two first oscillations. In the "frequency response" method [3], the open end of the catheter is exposed to strictly sinusoidal pressure waves of increasing frequencies. As soon as resonance is achieved, the values of ω_n and ζ are deduced from the resonance amplitude and frequency. The main objective of the present study is to provide a time domain method to identify the parameters on the basis of the recorded values of any pressure waves (whatever the shape is) given through both the fluid-filled catheter and a tip-catheter (Sentron) taken as reference. The procedure also allows to evaluate the precision of the fit between the data and the theoretical second order linear system.

METHOD

We use the classical model which describes the relationship between the fluid-filled catheter pressure signal $P_c(t)$ and the input pressure $P(t)$ at the open end of the catheter, by means of the following equation :

$$d^2P_c/dt^2 + 2\omega_n \zeta\, dP_c/dt + \omega_n^2 P_c = C\,P(t) \qquad (1)$$

where C is a constant of proportionality depending on the calibrations of the two signals P_C and P. If these calibrations are coherent, i.e. if a constant steady input and its constant response are equal, C equals ω_n^2 (ω_n in rad.s^{-1}). However, this condition is not required to apply the method. The aim of the identification procedure is to find the values of ω_n, ζ and C so that equation (1) is satisfied at best by the P_c and P waves. Equivalently, equation (1) can be replaced by the one obtained after integration of both members :

$$IP = C_1\, IP_c + C_2\, P_{c,0} + C_3\, dP_{c,0} \qquad (2)$$

where IP and IP_c are respectively the integrals of P and P_c over the time interval [0,t], and where $P_{c,0}$ and $dP_{c,0}$ are the variations of P_c and dP_c/dt on this interval. The constants C_i (i=1,...,3) are related to the parameters of the model through the following relations :

$$\omega_n^2 = C_1 / C_3 \qquad \zeta = C_2 / 2\, C_3\, \omega_n \qquad C = 1/ C_3 \qquad (3)$$

Fitting the model is to choose the values of the C_i's in order that the data satisfy equation (2) at best at every time step. We suggest to choose the values that minimize the sum of the squared differences between the two members of this equation, called the Residual Sum of Squares RSS :

$$RSS = \Sigma\,(IP - C_1\, IP_c - C_2\, P_{c,0} - C_3\, dP_{c,0})^2 \qquad (4)$$

In this way, the problem of fitting the model is equivalent to a multiple regression. The relations (3) allow to estimate ω_n, ζ and C from the regression coefficients C_i 's. The quality of the fit can be appreciated using the statistics associated to the regression.

If $p_c(\omega)$ and $p(\omega)$ are the complex amplitudes at frequency ω of the P_c and P waves respectively, the following relation holds between them :

$$p(\omega) / p_c(\omega) = (\omega_n^2 - \omega^2 + 2i\, \omega\, \omega_n\, \zeta)/C \qquad (5)$$

which allows the reconstruction of the spectrum $p(\omega)$ of P from the spectrum $p_c(\omega)$ of P_c.

To study the reproducibility of the estimated values of the parameters and to assess their independence from the shape of the input pressure wave, our experimental procedure was applied to 10 different shapes of input pressure waves. The input pressure was measured by a tip-catheter (Sentron). The fluid-filled catheter (Schwan-Ganz) was connected to a pressure transducer. Data were recorded by an appropriate software (Codas, DataQ instruments inc. Ohio, USA). To compare our method of identification with the "pop-test" method [1], we generated 9 step-signals and we estimated the values of ω_n and ζ by both methods. Student t-tests for paired data were used to compare de means.

RESULTS

Figure 1 gives an example of the pressure waves P_c and P recorded through the fluid-filled catheter and the tip-catheter.

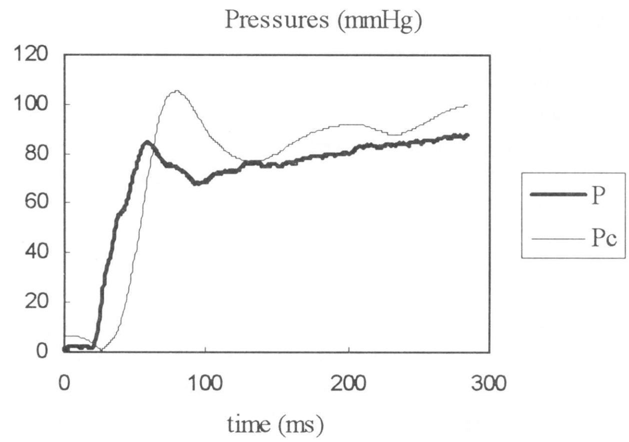

Figure 1. Recorded P_c and P pressure waves.

Table 1 gives the mean, standard deviation, minimum, maximum and the coefficient of variation of the parameters ω_n , ζ and C over the 10 experiments. In all the experiments the fit of the model with the data was excellent (coefficient of determination $R^2 > 0.99$).

Table 1. Results of the reproducibility analysis.

	Mean	SD	Min	Max	CV%
$\omega_n/2\pi$ (Hz)	11.51	0.701	10.75	12.61	6
ζ (rad)	0.432	0.042	0.383	0.503	10
C ($rad^2 . s^{-2}$)	5982	752	5148	7164	13

Table 2 gives the mean and standard deviation of ω_n and ζ estimated by our method and the "pop-test" method. The p-values associated to the t-tests for paired samples, are also given. No significant difference appeared between the means estimated by the two methods for both ω_n and ζ. However, the standard deviations are larger in the "pop-test" method.

Table 2. Comparison with the "pop-test" method.

	Proposed method		"Pop-test" method		
	Mean	SD	Mean	SD	p-value
$\omega_n/2\pi$	10.67	0.658	10.31	1.674	0.45
ζ	0.253	0.042	0.289	0.114	0.35

DISCUSSION

The "pop-test" method is based on the comparison of the theoretical response to a perfect step change of the input pressure. Experiments with tip-catheter shows that such a step change in pressure is difficult to generate and that the estimation of ω_n and ζ (especially ζ) can be sensitive to the shape of the generated signal. This appeared in the reproducibility study where classical "pop-test" equations [1] could not be applied in most cases. The "frequency response" method requires an expensive pressure generator, the procedure is rather long and must be carefully worked out. Therefore we investigated a new procedure able to estimate the parameters, whatever the shape of the input pressure wave is, and to evaluate how the model fits the data. In practice, our method does not require a tip-catheter. In a bench test, the reference pressure wave can be equally measured by a classical external pressure transducer connected as near as possible of the input of the fluid-filled catheter to be tested.

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