AN AUTOMATIC DIFFERENTIATION METHOD FOR INVESTIGATING INTRAVENTRICULAR PRESSURE IN THE HEART

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Measurement of the first and second derivatives of the intraventricular pressure is of particular interest in cardiology because, as some authors have described, it enables the contractile function of the myocardium to be assessed in the various phases of the cardiac cycle [1-7].

The method of obtaining derivatives by constructing tangents is associated with difficulties and with considerable error of measurements. The wiser application of automatic differentiation is prevented by the low level of noise suppression of existing instruments, and by absence of reliable, or indeed of any, methods of calibration. A medical differentiator must be equipped with a device for suppressing noise of industrial frequency (50 cps) and of its harmonics.

In the type DÉ-1 electronic differentiator which we used in this investigation incorporated an active transistorized low-frequency filter with a cutoff frequency of 30 cps, reducing interference from the supply system by a factor of at least 100, but giving minimal distortion of the shape of the useful signal. In this way high-quality tracings could be obtained of the first and second derivatives of the intraventricular pressure and of the ECG, regardless of the intensity of interference from the supply system.

For quantitative analysis of the result of differentiation, a sinusoidal calibration voltage generator was introduced into the circuit of the differentiator, producing a voltage at the input of the differentiator when in the "calibration" position, expressed by the equation:

$$U_0(t) = U_{0C} \cdot \sin \omega t, \tag{1}$$

where U_{0C} represents the amplitude of the sinusoidal calibration signal (V), and ω its angular frequency.

The first and second derivatives of the calibration signal are determined at the output of the recording instrument by:

$$U_1(t) = A_1 \cdot \omega \cdot U_{0C} \cdot \cos \omega t, \tag{2}$$

$$U_2(t) = A_2 \cdot \omega^2 \cdot U_{0C} \cdot \sin \omega t, \tag{3}$$

where A_1 represents the constant coefficient of transmission of the circuit of the first derivative (including the recording instrument), and A_2 represents the same for the second derivative.

The amplitude values $U_1(t)$ and $U_2(t)$ are expressed in volts/sec and volts/sec^2 respectively, and are given by:

$$U_{1C} = A_1 \cdot U_{0C} \cdot \omega, \tag{4}$$

$$U_{2C} = A_2 \cdot U_{0C} \cdot \omega^2. \tag{5}$$

An advantage of the calibration method described is the high accuracy of the measurements and the simplicity of the calibrator circuit. The accuracy of calibration is determined by the stability of the frequency and amplitude of the calibration voltage.

At the end of calibration, instead of the calibration signal the test signal X(t) is fed into the input of the differentiator. Its derivatives are given by:

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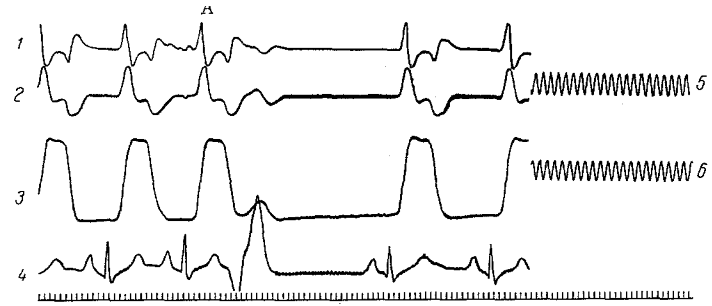

Fig. 1. Synchronized tracing of first and second derivatives of pressure inside the left ventricle of a dog. 1) Second derivative; 2) first derivative; 3) pressure within left ventricle; 4) ECG (lead II); 5) second derivative of calibration signal; 6) first derivative of calibration signal. Calculations for complex denoted by A in the text.

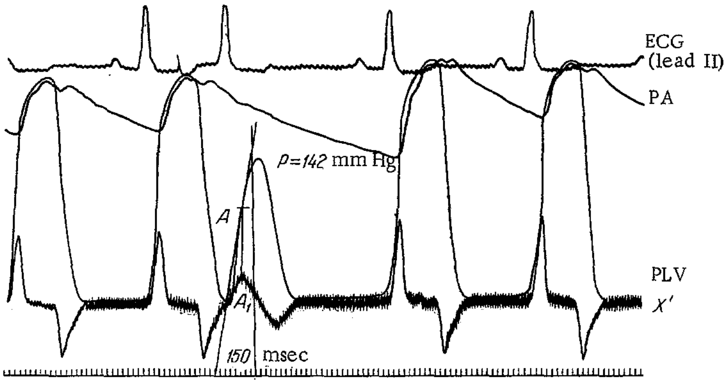

Fig. 2. Determination of rate of increase of pressure at point A of an atrial extrasystole by the method of drawing a tangent at this point and by means of automatic differentiation. PA) pressure in aorta; PLV) pressure in left ventricle; point A_1) maximal velocity of pressure increase corresponding to point A on intraventricular pressure curve.

$$V_1(t) = A_1 \cdot X'(t), \tag{6}$$

$$V_2(t) = A_2 \cdot X''(t), \tag{7}$$

where X'(t) and X"(t) are the required velocity and acceleration of the differential signal, V_1(t) and V_2(t) represent the voltages (currents) of the first and second derivatives of the test signal in the recording circuit.

Comparing Eqs. 4, 6 and 5, 7 in pairs, and eliminating A_1 and A_2, we obtain:

$$X'(t) = \frac{V_1(t)}{U_{1C}} \cdot U_{0C} \cdot \omega \ (\text{V/sec}), \tag{8}$$

$$X''(t) = \frac{V_2(t)}{U_{2C}} \cdot U_{0C} \cdot \omega^2 (\text{V/sec}^2). \tag{9}$$

To calculate the velocity and acceleration of the intraventricular pressure in mm Hg, the electromanometer must be calibrated before the beginning of the experiment by a static signal, the voltage at the input of the differentiator being measured simultaneously.

As a result, a correcting coefficient B is obtained, enabling values expressed in V/sec to be converted into value expressed in mm Hg/sec.

The final equations for calculating the velocity and acceleration of the pressure change assume the form:

$$X'(t) = \frac{V_1(t)}{U_{1C}} \cdot U_{0C} \cdot \omega \cdot B \text{ mm Hg/sec}, \tag{10}$$

$$X''(t) = \frac{V_2(t)}{U_{2C}} \cdot U_{0C} \cdot \omega \cdot B \text{ mm Hg/sec}^2.* \tag{11}$$

Let us consider examples of determination of the maximal rate of increase of pressure in the left ventricle of a dog. In the experiments from which the curves shown in Fig. 1 were taken, $V_{1Amax} = 8$ mm, $U_{1C} = 9$ mm, $V_{1Amax} = 6.5$ mm, $U_{2C} = 9$ mm, $\omega = 157$/sec, and B = 2 mm Hg/mV. Calculation by Eqs. (10) and (11) showed that the maximal rate of rise of pressure in the left ventricle during normal systole is 1400 mm Hg/sec and the maximal acceleration is 178,000 mm Hg/sec^2. Graphic analysis of the maximal velocity in this experiment was complicated by the fact that it was difficult to construct a tangent on the curve of intraventricular pressure accurately at the point corresponding to the maximum of $\Delta P/\Delta t$.

In another case at the onset of an extrasystole, we were able to calculate the rate of rise of pressure both by means of an electronic differentiator and graphically (Fig. 2). In this case the value of the rate of increase of pressure at point A, calculated by the equation, was 982 mm Hg/sec compared with 946 mm Hg/sec determined graphically.

When calculating the rate and acceleration of fall of pressure, the same equations can be used but with a minus sign. The maximal negative velocity in Fig. 2 is $X' = -1220$ mm Hg/sec, and the maximal negative acceleration $X'' = -200{,}000$ mm Hg/sec^2.

In experiments on dogs with the chest closed and under morphine-urethane anesthesia the values of the maximal rate of increase of pressure were 1500-4000 mm Hg/sec, in agreement with the data of Reeves and co-workers (1960) [4]. The maximal rate of fall of pressure varied within the same limits in different experiments. The maximal positive and negative acceleration in our experiments were 200,000 and $-350{,}000$ mm Hg/sec^2 respectively.

On comparing these indices with the phases of cardiac activity it may be seen that the velocity of pressure increase reaches a maximum at the beginning of the ejection period, while acceleration reaches a maximum in the first half of the phase of isometric contraction. The fall of pressure reaches its maximum at the end of the ejection period. Zero velocity of pressure change may evidently be used to mark the boundary between the phases of fast and slow ejection.

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*Usually the values of $V_1(t)$, $V_2(t)$, U_{1C}, and U_{2C} may be measured in mm on the tape of the automatic recorder.