METHODS

Method for Assessing the Stroke-to-Stroke Biomechanical Characteristics of Coronary Vessels

D. V. Borovikov and V. L. Golubykh

Translated from Byulleten' *Eksperimental'noi Biologii i Meditsiny*, Vol. 122, No. 11, pp. 594-597, November, 1996
Original article submitted April 12, 1995

The biomechanical parameters of coronary vessels are estimated in a model of the coronary input impedance. The model includes the capacity of epicardial vessels, input resistance, limiting resistance, and some sources of electromotive force symbolizing the intramyocardial and critical pressure values. The theoretical value of coronary blood flow is calculated from computer-optimized parameters of the model and experimental curves representing arterial pressure and left-ventricular pressure. The theoretical and experimental curves of coronary blood flow are in good agreement both during the maximum vasodilatation and in intact tone. The basic parameters, such as epicardial vessel pliability, zero blood flow pressure, and resistance of the resistive portion of blood vessels corresponded to previous evaluations. The dispersion of calculated stroke-to-stroke parameters is 5-10%.

Key Words: *coronary bed model; zero blood flow pressure; coronary vessel capacity; coronary blood flow*

Coronary blood flow has a number of specific features. The heart not only pumps blood into circulation but also prevents back flow into the heart chambers. That is why the total capacity of the coronary bed (the mean resistance) is determined not only by its state, but also by the force and rate of cardiac contractions. One of the ways to rule out the effects of extravascular compression on the measured resistance is calculation of end diastolic resistance as the ratio between arterial pressure (AP) and coronary blood flow (CF) at the end of diastole [4].

Numerous experiments show that CF is arrested if AP drops to the value much higher than venous pressure. This value was denoted as zero blood flow pressure or critical pressure (P_{zf}). For intact coronary vessels P_{zf} is about 40 mm Hg; the ratio between pressure and blood flow during pressure drop is linear. From these data we concluded that P_{zf} should be taken into account when vascular resistance is calculated to estimate the pushing pressure, the resistance being determined by the slope of the flow rate curve [2]. Some drugs change the value of P_{zf}. Changes in P_{zf} and resistance are independent and even opposite [6]. End diastolic pressure depends on the moment of measurement, i.e., on the duration of diastole. Hence, critical pressure should be taken into account when coronary resistance is estimated [2].

The method of input-output characteristics requires experiments with induced arrhythmia, which diminishes the physiological validity of results. In a cardiac cycle of normal duration, the input-output values are strongly influenced by the capacity of coronary arteries. This capacity is a variable, and its effect is determined by the rate of AP reduction [3].

Our aim was to develop a method for estimating the main biomechanical characteristics of the coronary bed which affect CF. This method should be based

Institute of Experimental Cardiology, Cardiology Research Center, Russian Academy of Medical Sciences, Moscow

0007-4888/96/0011-1165$15.00

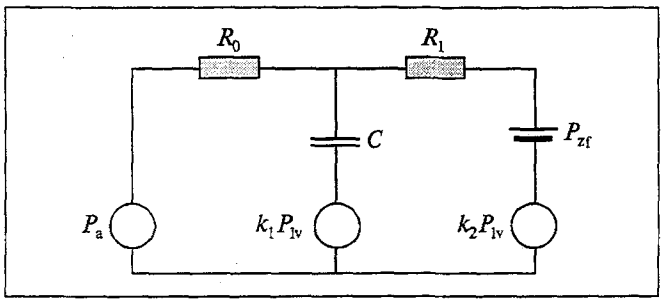

Fig. 1. A schematic drawing of the coronary bed model represented as an electrical analog. P_a) aortic pressure , C) capacity, R_0) coronary artery resistance, R_1) resistance in the resistive portion of the bed, P_{zf}) critical pressure of blood flow arrest. The parameters characterizing systolic extravascular compression of large and small vessels, proportional pressure in the left ventricle (k_1P_{lv}, k_2P_{lv}).

on measurements performed during cardiac cycle without heart arrest or controlled perfusion of the coronary artery.

Previously, we proposed a coronary bed model adequately describing the CF curve [1]. However, the use of this model for the assessment of changes occurring in the circulation bed implies that there is a method for determining the model parameters based on measurements of pressure and CF, i.e., requires the solution of a reciprocal problem, which is impossible because of the presence of a nonlinear element (diode) and the ambiguity of the measured values caused by this presence. Therefore, we modified the model to preserve its benefits (the possibility of describing the CF curve) and to attain stability of parameters measured by the available methods. This became possible after analysis of the constant value of time needed for recharging the intramyocardial capacity of the coronary bed, (3-5 sec, depending on the condition of determination) [8]. At normal heart rate (50-60 beats/min in dogs) peripheral vessels are not critically occluded, i.e., the diode is unnecessary. Figure 1 is a schematic drawing of such a model.

In this model, CF (deduced as described [1]) in the $R_0 \ll R_1$ approximation can be calculated as follows:

$$Cf(t) = -R_0 C \frac{dCf}{dt} + C\frac{dP_a}{dt} - Ck_1\frac{dP_{lv}}{dt} + \frac{P_a}{R_1} - \frac{P_{zf}}{R_1}K_2\frac{P_{lv}}{R_1} \quad (1)$$

Equation (1) can be written as:

$$\sum_k P_k A_k - Cf = 0$$

where P_k are the measured values and A_k is the unknown parameters. Unambiguity of the measured values and stability of solution in terms of the least squares method is determined by linear independence of P_k function in the chosen interval of measurements.

MATERIALS AND METHODS

Acute experiments were carried out on mongrel dogs of both sexes (body weight about 12 kg) under hexenal anesthesia (50 mg/kg) with droperidol premedication (5 mg/kg). After tracheotomy and intubation, a PO-5 apparatus for artificial ventilation of the lungs was applied. The thorax was opened in the fourth intercostal area. A sensor of an SP2201 STATHAM electromagnetic flowmeter was placed on the circumflex branch of the left coronary artery. For the blood pressure measurements, a catheter was passed through the carotid artery and inserted into the left ventricle through its wall. Adenosine was infused in the coronary artery through a catheter with a metal needle at the end, which was inserted in the coronary artery. HP 1280C sensors were used for the blood pressure measurements. The coronary flow curves and blood pressure in the aorta and left ventricle were recorded using an HP 7758D polygraph with parallel digitation. Vasodilatation was provoked by controlled infusion of adenosine in the coronary artery, the rate

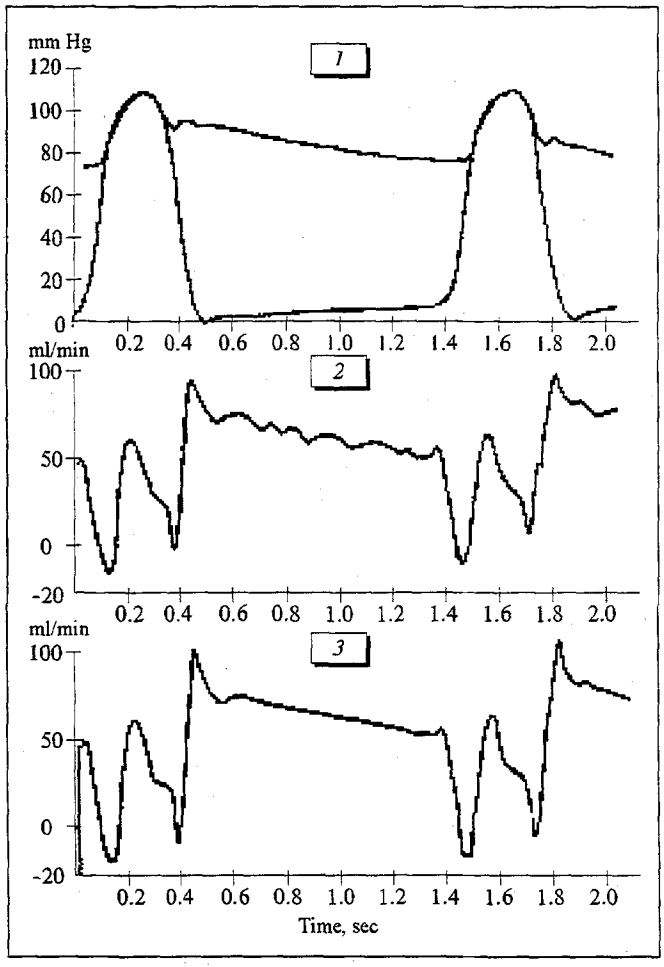

Fig. 2. Comparison of experimental CF curve (2) with calculated $C_f(t)$ curve (3) based on the AP and left ventricular pressure curves (1).

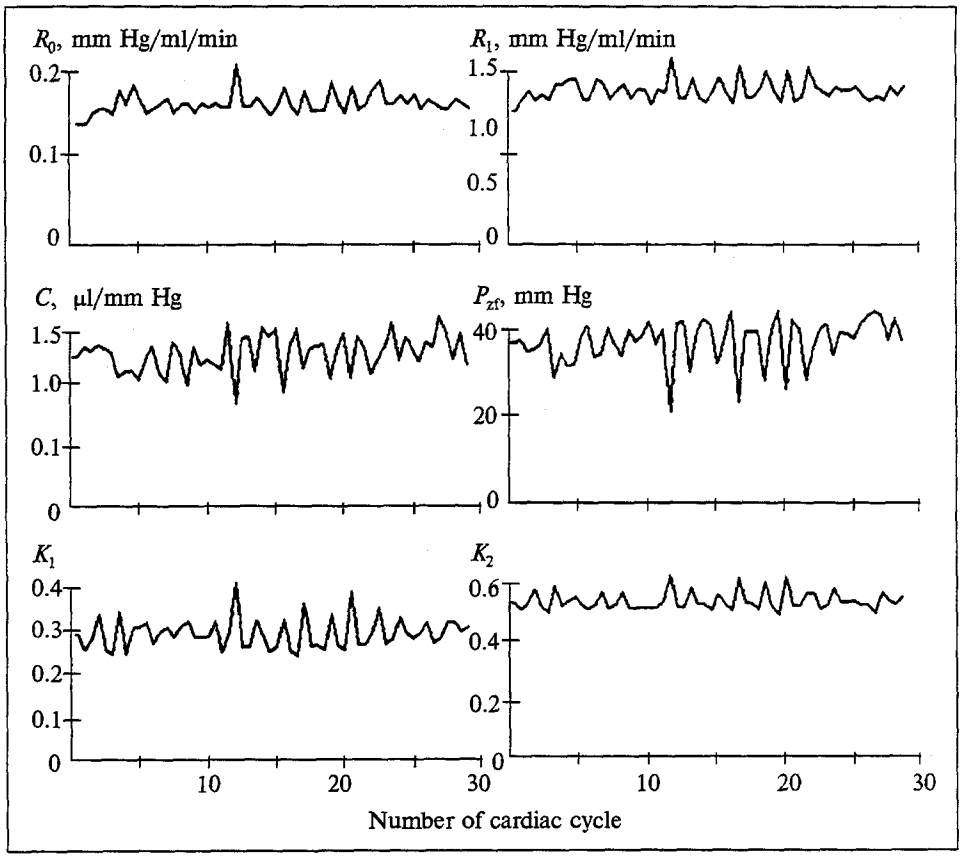

Fig. 3. Calculation of the stroke-to-stroke model parameters.

of infusion being proportional to the mean blood flow; therefore, the concentration of adenosine was constant (5 μg/ml). Digitation of data, processing of signals, and monitoring of infusion were carried out with a microcomputer.

The aortic and left ventricular pressure curves were used to solve the Cauchy problem with the rectangle formula at 1/100 intervals and digitation frequency of 500 Hz. The initial conditions were as follows:

$$t_0=0: Cf=Cf(0);$$

$$Cf(t)=Cf(t_0)e^{-t/R_0C}+(1/R_0C)e^{-t/R_0C}\int F(t)e^{\tau/R_0C}\,d\tau.$$

where

$$F(t)=C(dP_a/dt)-Ck_1(dP_{lv}/dt)+(P_a/R_1)-(P_{zf}/R_1)-K_2(P_{lv}/R_1).$$

The parameters were selected by searching for the minimal sum of square deviations of the theoretical CF (Cf) curve from the experimental curve over several heart cycles. Minimization was performed by the simplex method (Nelder-Mead algorithm) [7].

RESULTS

The calculated and measured curves practically did not differ in all experiments (Fig. 2). The model parameters for the intact bed were as follows: R_0=0.15±0.03 mm Hg/ml/min, C=1.43±0.11 μl/mm Hg, R_1=1.24±0.13 mm Hg/ml/min, P_{zf}=34.2±2.3 mm Hg, K_1=0.32±0.04, K_2=0.51±0.06; under conditions of adenosine vasodilatation the parameters were: R_0=0.04±0.01 mm Hg/ml/min, C=5.37±0.34 μl/mm Hg, R_1=0.24±0.05 mm Hg/ml/min, P_{zf}=13.2±1.4 mm Hg, K_1=0.82±0.24, K_2=0.73±0.04.

The resistance, zero blood flow pressure, and capacity of coronary arteries measured in previous experiments were consistent with those measured for both intact vessels and maximum vasodilatation in other experiments [5]. It can be concluded that our model is adequate for description of CF, and parameters calculated with the use of this model correspond to the biomechanical characteristics of coronary vessels. Analysis showed that the reciprocal problem is well conditioned, and its solution is stable, which is illustrated by calculation of the stroke-to-stroke parameters (Fig. 3). The dispersion is 5-15%, which indicates linear independence of function P_k and unambiguity of the estimates.

Thus, the proposed method allows one to assess the main biomechanical parameters of coronary vessels during experiment without using any interventions. On the other hand, when interpreting the results, it should be remembered that this method is based on

a model with lumped parameters, while in reality resistance and pliability are distributed along blood vessels.

REFERENCES

1. D. V. Borovikov and V. L. Golubykh, *Byull. Eksp. Biol. Med.*, **106**, No. 10, 397-399 (1988).
2. R. F. Bellamy, *Cardiovasc. Res.*, **43**, 92-101 (1978).
3. C. Eng, J. H. Jetzer, and E. S. Kirk, *Circ. Res.*, **50**, 334-341 (1982).
4. D. E. Gregg, H. D. Green, and C. Wiggers, *Am. J. Physiol.*, **112**, 362-373 (1965).
5. R. M. Judd and R. E. Mates, *Ibid.*, **260**, H1841-H1851 (1991).
6. F. J. Klocke, R. E. Mates, J. M. Canty, *et al.*, *Circ. Res.*, **56**, 310-323 (1985).
7. J. A. Nelder and R. Mead, *Comp. J.*, **7**, 308-313 (1965).
8. J. A. E. Spaan, N. W. Breuls, and J. D. Laird, *Circ. Res.*, **49**, 584-593 (1981).

Live Tissue Surrogate for Surgical Laser Testing

A. I. Nevorotin, A. A. Zhloba, I. K. Il'yasov, V. V. Tomson, and G. Yu. Yukina

Translated from *Byulleten' Eksperimental'noi Biologii i Meditsiny*, Vol. 122, No. 11, pp. 597-600, November, 1996
Original article submitted September 23, 1995

Live tissue surrogate is proposed, consisting of a filler, egg albumen, donor blood, and glycerol. When exposed to an Nd-YAG laser operating at a wavelength of 1064 nm in pulsed or permanent modes, the surrogate changes color, which allows one to determine the borderline parameters of radiation causing thermal necrosis and to select the optimal conditions of laser surgery. The sensitivity of the live tissue surrogate to the working power range is close to that of live tissue containing blood.

Key Words: *surgical lasers; tissue surrogate; thermal necrosis*

Recently, lasers have found a wide application in surgery. However, lasers (CO_2, 532, 1032, or 1064 nm Nd-YAG, argon, etc.) cause thermal necrosis while operating in the destruction and coagulation modes. This necrosis provides "welding" of tissues [3], their sterility [11] and ablasty [8], and intraoperative hemostasis [13,10]. However, deep thermal denaturation caused by laser surgery may have unfavorable consequences, such as prolongation of the regeneration period due to decelerated resorption of large volumes of necrotic tissue [1,9]. Optimal conditions for clinical application of lasers can be selected after labor- and time-consuming operations on tissues of laboratory animals. Various surrogates of live tissues (TS) have been tried for preclinical experiments with lasers, such as egg albumen and yolk, gels, some plastics, etc. [5,14,15]. We propose a new surrogate which is better approximated to live tissues. This TS permits rapid, accurate, and well reproducible assessment of the effect of surgical lasers.

Research Center, I. P. Pavlov State Medical University, St. Petersburg

MATERIALS AND METHODS

Nd-YAG lasers operating in the permanent (Raduga) and pulsed (laboratory installation) modes at a wavelength of 1064 nm were used. Tissue surrogate was exposed to long-distance and contact irradiation through a quartz light guide (diameter 400 nm); hepatic tissue of narcotized white rats served as a control. Egg albumen was the main component of TS. When irradiated beyond the denaturation threshold, the TS changes color and becomes insoluble and compact; these qualities are often used for laser tests [14]. The composition of TS is as follows: 20 ml egg albumen, 2.5 ml glycerol, 4.5 ml donor blood (blood with expired storage term), and 10 g filler (ion-exchange resin on cellulose). The ingredients should be thoroughly mixed to obtain evenly colored thick

0007-4888/96/0011-1168$15.00