A METHOD FOR ESTIMATING THE PHYSIOLOGICAL SIGNIFICANCE OF EACH OF SERIAL VASCULAR LESIONS

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Abstract - The physiological severity of a stenosis is determined by its fractional flow reserve (FFR). Coronary arteriosclerosis is a diffuse disease, and it is not uncommon for 2-3 serial lesions to be observed in the same vessel. Direct measurement of the physiological severity of each lesion is impossible due to the hemodynamic interaction between them. The "true FFR" of a given lesion is defined as the FFR that would be measured if other stenoses in the same vessel were absent. Applying the hypothesis that the pressure gradient across a stenosis is proportional to the square of the flow, we obtained equations that are non-sensitive to collateral flow. We applied these equations to the human data of 32 patients with tandem stenoses that were presented by Pijls et al.. The correlation between the true FFR calculated by the suggested method and the FFR measured after treatment of one of the lesions for all 32 patients was significant (R=0.9).

Keywords - Coronary stenosis, fractional flow reserve, coronary physiology.

I. INTRODUCTION

The physiological severity of a stenosis is determined by its fractional flow reserve (FFR). The FFR is a ratio of the hyperemic blood flow in a stenotic vessel to the hyperemic flow in a stenosis-free vessel. Coronary arteriosclerosis is a diffuse disease, and it is not uncommon for 2-3 serial lesions in the same vessel to be observed in clinical practice. Direct measurement of the physiological severity of each lesion is impossible due to the hemodynamic interaction between them. The "true FFR" of a given lesion is defined as the FFR that would be measured if other stenoses in the same vessel were absent. Pijls et al.[1] recently proposed a new method for the calculation of the true FFR of each lesion in the case of a tandem lesion. The obtained equations allowed the estimation of the true FFR of each lesion but only if the wedge pressure were known, meaning after treatment of one of the multiple lesions. The equations reported by Pijls et al. [1] were based on the linear pressure-flow relation across a stenosis. We had earlier suggested that the pressure gradient across a stenosis is proportional to the square of the flow [2]. Applying this hypothesis to a case of a tandem lesion, we obtained equations that are less sensitive to collateral flows. The true FFR may then be calculated by using the measured values of the hyperemic pressures only, without needing to know the wedge pressure.

When there is a side branch between stenoses, the effect of branch steal [1] precludes the calculation of the true FFR of the individual lesion by means of hyperemic pressure measurements alone. In the present paper, we obtained equations allowing the calculation of the true FFR in such cases, under the condition that the coronary flow reserve (CFR) across each lesion is known. The method of making the CFR calculation using pressure measurements was described earlier [2].

II. THE MATHEMATICAL MODEL.

The flow in a coronary blood vessel with N serial stenoses is analyzed. P_0 is the aortic pressure, P_i is the pressure measured distal to stenosis number i measured during maximal hyperemia, R_v is minimal vascular bed resistance (i.e., resistance achieved during maximum hyperemia), and Q_N is the hyperemic flow in a vessel with N stenoses. Partial FFR of the first k lesions ($pFFR_k$) was defined as the ratio of the hyperemic pressure distal to stenosis number k to the aortic pressure:

$$pFFR_k = P_k/P_0 \quad , k=1,\ldots,N. \quad (1)$$

The FFR of all the lesions in combination is $pFFR_N$. The vascular bed is assumed as being purely resistive, thus

$$pFFR_N = (Q_N + Q_{c,N})/Q_{max} \quad (2)$$

where $Q_N + Q_{c,N}$ and Q_{max} are hyperemic flows through the vascular bed in the vessel with N serial stenoses and in a non-stenotic vessel, respectively, and $Q_{c,N}$ is the collateral flow.

The pressure gradient across stenosis ΔP is assumed to be proportional to the square of the flow Q:

$$\Delta P = \alpha Q^2 \quad (3)$$

where the constant α is a function of the stenosis geometry only.

In the case of serial stenoses without collaterals ($Q_{c,N}=0$), the flow Q through each stenosis and vascular bed is the same and equal to Q_N. Applying the equations (1-3) to lesion number k yields:

$$\frac{pFFR_k - pFFR_{k-1}}{pFFR_N^2} = \frac{\alpha_k Q_{max}^2}{P_0}, k = 1,\ldots, N \quad (4)$$

If only lesion k exists in the blood vessel, then the hyperemic flow $Q_k = FFR_k Q_{max}$, where FFR_k is the true FFR of lesion k. The pressure-flow relation across the lesion may be expressed as:

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Abstract

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$$\frac{1 - FFR_k}{FFR_k^2} = \frac{\alpha_k Q_{max}^2}{P_0}, \, k = 1,..., \, N \qquad (5)$$

The right hand sides of the equations (4) and (5) are the same. Hence, their left hand sides are equal, thereby resulting in a quadratic equation for the true FFR:

$$\frac{1 - FFR_k}{FFR_k^2} = \frac{pFFR_k - pFFR_{k-1}}{pFFR_N^2}, \, k=1,...,N. \qquad (6)$$

The last equation allows the calculation of the true FFR of lesion k based on four pressure measurements during maximal hyperemia. The method may be generalized for coronary vessels with collateral flows and for a case of a small side branch between lesions.

III. RESULTS.

We applied equation (5) to the human data of 32 patients with tandem stenoses that were presented in Table 2 of Pijls et al.'s study [1]. The correlation between the true FFR as calculated by eq. (5) and the FFR measured after treatment of one of the lesions for all 32 patients was significant (R=0.9).
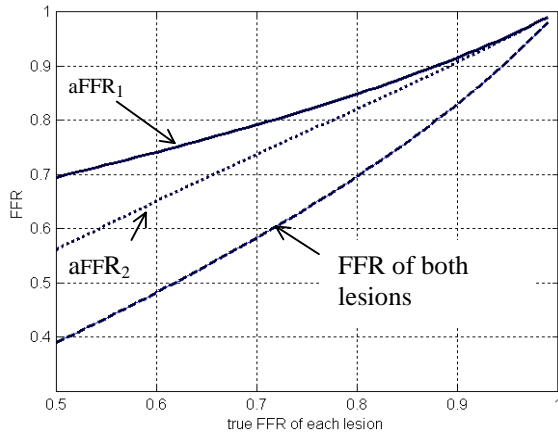
The suggested equations allow the estimation of the hemodynamic interaction between lesions. The following is an example of an analysis of an artery with 2 equal stenoses, each having the same true FFR (FFR_1=FFR_2=FFR). The equations (5) allow calculating of the FFR of both lesions together ($pFFR_2$) and partial FFR of the first lesion. The apparent FFR of the lesion i ($aFFR_i$) is defined as the ratio of the pressures distal and proximal to the lesion measured during maximum hyperemia. $aFFR_i$=$pFFR_i$/$pFFR_{i-1}$. The calculated values of the FFR of both lesions and apparent FFR of each lesion are presented in the figure.

This example explains the significant growth of the hyperemic pressure gradient across the first lesion after stenting of the second lesion that is sometimes observed in clinical practice.

IV. CONCLUSION.

Quadratic equations allowing the calculation of the true FFR of each stenosis in serial stenoses are proposed. The equations allow for the calculation of the true FFR if hyperemic pressure is measured distal to each lesion.

REFERENCES.

[1] Pijls NJH, De Bruyne B, Bech GJW, Liistro F, Heyndrickx GR, Bonnier HJRM, Koolen JJ. Coronary pressure measurement to assess the hemodynamic significance of serial stenoses within one coronary artery. Validation in humans. *Circulation*, vol.102, pp. 2371-2377. 2000

[2] Shalman E., Barak C., Dgany E., Noskowitz H., Einav S., Rosenfeld M. Prssure- based simultaneous CFR and FFR measurements: Understanding physiology of stenosed vessel. *Computers in Biology and Medicine*, vol.31. pp 353-364, 2001