Analytically Computed Fractional Flow Reserve based on Coronary CT Angiography

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Abstract: Invasively determined Fractional Flow Reserve (FFR) has been recognized as a reliable tool for assessing coronary artery stenosis severity. Since the invasive method is associated with a risk of vessel injury due to pressure wire manipulation several non-invasive techniques have been developed. The objective of this paper is to propose an alternative, much less time-consuming, analytical solution based on Computed Tomography Angiography (CTA) images and the overall pressure drop calculation across the stenosis in the coronary artery.
The results obtained using this method are validated by comparing them with the clinical data for patients who underwent invasive coronary angiography as well as with the results obtained by using CFD simulation. FFR determined using the analytical method compared with the clinical and CFD ones differs by 4.5% and 3.9% respectively. This confirms that the analytically determined FFR can be reliable for the physiological assessment of coronary artery stenosis.

Keywords: coronary artery stenosis, fractional flow reserve, analytical method, CTA images

1. Introduction

Cardiovascular diseases (CVDs) refer to any type of disturbance in the normal functioning of the heart and blood vessels [1] whose frequency has dramatically increased in the modern world as a consequence of overall global trends (social, economic, demographic, etc.) [2]. Coronary artery disease (CAD) represents the most common type of cardiovascular disease. The cause of this disease in more than 95% of cases is atherosclerosis, which occurs in coronary arteries as a result of the deposition of cholesterol, fibrous tissue, calcium and other substances contained in the blood [3]. This results in the appearance of atherosclerotic plaque inside blood vessels (Fig. 1) which forms a barrier (stenosis) that restricts the blood flow to the heart and causes myocardial ischemia, the most prevalent risk factor associated with adverse clinical outcomes.

A number of methods, such as *Invasive Coronary Angiography (ICA), Myocardial scintigraphy (MS), Magnetic Resonance Imaging (MRI) and Computed Tomography Coronary Angiography (CTCA)* can be used for the diagnosis and monitoring of coronary artery disease. However, all these methods rely on visual assessment of coronary artery obstruction and are unable to directly assess its hemodynamic significance.

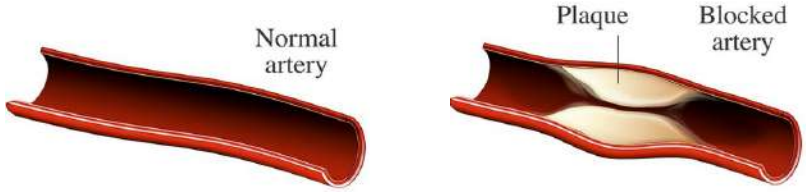

Figure 1. Coronary artery disease [4]

In order to overcome these shortcomings additional algorithms have been developed to enhance the assessment of coronary stenoses severity and make the best possible decisions about further steps in the treatment of patients (medical therapy or percutaneous or surgical revascularization) [5].

2. Determination of Fractional flow reserve (FFR)

Fractional flow reserve (FFR), first proposed by Pijls [6], represents a significant advance in assessing the functional significance of coronary artery stenosis. FFR is based on the fact that stenosis causes a pressure drop proportional to the narrowing of the cross-section caused by the formed plaque. FFR is calculated as [7]:

$$FFR = \frac{P_a - \Delta P}{P_a} \tag{1}$$

where P_a is proximal arterial pressure (equal to aortic pressure) and ΔP is the overall pressure loss along the vessel segment.

The overall pressure loss consists of four losses (due to flow convection, constriction at the entrance of stenosis, flow diffusion and expansion post-stenosis).

The pressure drops due to flow convection can be expressed as [8]:

$$\Delta P_{conv} = \frac{\rho}{2}\left(V_{out}^2 - V_{in}^2\right) = \frac{\rho Q^2}{2}\left(\frac{1}{A_{out}^2} - \frac{1}{A_{in}^2}\right) \tag{2}$$

where ρ, V and Q are blood density, blood velocity and flow rate, while A_{in} and A_{out} represent the cross sectional areas proximal and distal to stenosis.

In the case of fully developed flow, the pressure drop due to constriction is [9]:

$$\Delta P_{contr} = \frac{\rho Q^2}{2}\frac{1}{2}\left(\frac{1}{A_{sten}^{8/3}} - \frac{1}{A_{prox}A_{sten}^{5/3}}\right)^{3/4} \tag{3}$$

where A_{sten} and A_{prox} the sectional areas of stenosis and artery proximal to stenosis.

The pressure drop due to flow diffusion which is caused by viscosity, initiates flow acceleration. If we suppose an inviscid flow core (with a uniform velocity) at the entrance of stenosis defined by a dimensionless radius φ which can be calculated by [10]:

$$\frac{\pi\mu L_{sten}}{4\rho Q}=\frac{1}{4}\int_{\varphi}^{1}\frac{(1-\varphi)(6+\varphi)\left(1+4\varphi+9\varphi^2+4\varphi^3\right)}{5\varphi(3+2\varphi)\left(3+2\varphi+\varphi^2\right)^2}d\varphi \tag{4}$$

In case φ < 0.05, that is usual for coronary artery, the pressure drop due to diffusion is:

$$\Delta P_{diff}^{vess}=\frac{\rho Q^2}{2A_{sten}^2}\frac{96}{5}\int_{\varphi}^{1}\frac{\left(1+4\varphi+9\varphi^2+4\varphi^3\right)}{\varphi(3+2\varphi)\left(3+2\varphi+\varphi^2\right)^2}d\varphi+\int_{0}^{L_{vess}-L_{entr}}\frac{8\pi\mu Q}{A_{in}^2}dx \tag{5}$$

while the pressure drop due to sudden expansion is:

$$\Delta P_{exp}^{par}=\rho Q^2\left[\left(\frac{1}{A_{sten}}-\frac{1}{A_{dist}}\right)\left(\frac{1}{A_{sten}}-\frac{1}{3}\frac{1}{A_{dist}}\right)\right] \tag{6}$$

The total pressure drop is calculated as the sum of (2), (3), (4) and (6):

$$\Delta P=\Delta P_{conv}+\Delta P_{contr}+\Delta P_{diff}+\Delta P_{exp} \tag{7}$$

All needed anatomic parameters (diameters, lengths, areas, etc.) were taken from the corresponding artery models reconstructed from CTA images.

3. Results

Using the presented analytical model, FFR values were computed for 20 patients. These values are compared with the corresponding medical (experimental) values obtained by the invasive method. Figure 1 shows the relationship between the medical results (mFFR) and the results obtained by the proposed analytical method (aFFR). A linear least-squares fit method gave the relation mFFR = 0.041 + 0.972·aFFR. The coefficient of determination is $R^2 =$ 0.854. A relatively small deviation of the results in relation to the regression line is observed.

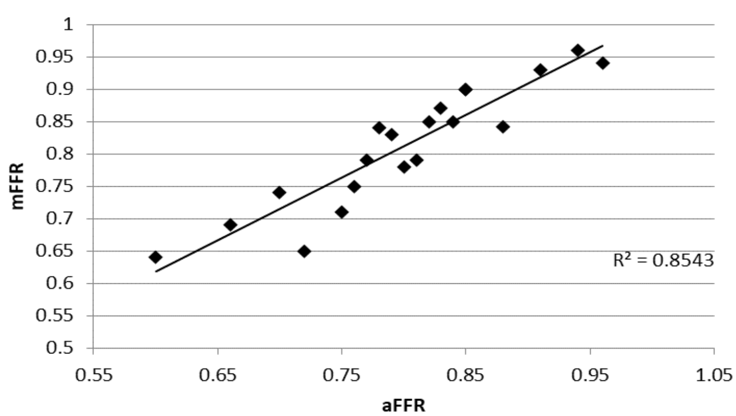

Figure 1. A relationship between medical and analytical FRR.

4. Conclusion

The presented analytical model is based on conservation of energy, which takes into account various energy (pressure) losses along the stenosis. It calculates non-invasive aFFR from CTA images data. This method was validated for 20 models of coronary arteries using the corresponding experimental data obtained by "gold standard" invasive measurement. A very good coefficient of determination (0,926) is observed in the entire range of FFR values. This confirms that the presented analytical model can reliably assess the physiological significance of the stenosis, and accordingly, suggest further treatment of the patient. At the same time, this method requires significantly lower computation time.

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