Flow simulation of the intracoronary shunt tube for off-pump coronary artery bypass

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Received 15 October 2002; received in revised form 20 January 2003; accepted 3 February 2003

Abstract

Objective: To simulate blood flow provided by the intracoronary shunt tube, and to clarify whether this method is actually suitable for Off-pump coronary artery bypass (OPCAB), we investigated the efficacy of the intracoronary shunt tube in a theoretical model on the basis of fluid dynamics. Methods: Fluid dynamics analysis was performed to simulate flow decrease after attachment on an intracoronary shunt model. Results: The flow ratio in the case of turbulent flow is in proportion to the ratio of the inner diameter to the third power, and that in the case of laminar flow is in proportion to the ratio of the inner diameter to the sixth power. When this analysis is applied to commercial shunt tubes, coronary flow was estimated as approximately 2–14\% of pre-attachment flow in turbulent flow, and only less than 0.1\% in laminar flow. Conclusions: This result suggests that use of intracoronary shunt tubes in OPCAB may rarely contribute to maintenance of coronary flow, and they should be used carefully, especially in a jeopardized coronary artery.

Keywords: Off-pump coronary artery bypass grafting; Intracoronary shunt tube; Flow simulation; Fluid dynamics

1. Introduction

Off-pump coronary artery bypass (OPCAB) is becoming increasingly popular world-wide [1–4]. This procedure has several advantages over conventional coronary artery bypass grafting with cardiopulmonary bypass regarding mortality, morbidity, and cost-effectiveness [5,6]. However, concerns still exist regarding myocardial ischemia in the area supplied by the target vessel. Several methods have been devised to avoid or reduce myocardial ischemia during anastomosis, and at present the intracoronary shunt tube is the most popular for this purpose [7–9].

Indeed the use of the intracoronary shunt tube is easy and inexpensive, but the efficacy of this method is still unclear. The intracoronary shunt tube is designed to be placed at a distal site from the stenosis lesion, and this fact makes it difficult to evaluate the efficacy of the intracoronary shunt tube because the severity of the stenosis lesion is different from case to case in clinical situations. Even in experimental settings, quantitative evaluation of the intracoronary shunt tube is very difficult because it is difficult to make a definite proximal coronary artery stenosis.

In this study, we investigated the efficacy of the intracoronary shunt tube in a theoretical model on the basis of fluid mechanics. The purpose of this study is to simulate blood flow provided by the intracoronary shunt tube, and to clarify whether this method is actually suitable for OPCAB.

2. Methods

To analyze flow loss caused by attachment of an intracoronary shunt tube, a simple theoretical model was made (Fig. 1). In this model, the length of the coronary artery into which the shunt tube is to be inserted is denoted as \( L \), the inner diameter of the coronary artery as \( D \), and the inner diameter of the shunt tube as \( d \). The intracoronary pressure upstream and downstream at pre-attachment are represented as \( p_1 \) and \( p_2 \), respectively, and those at post-attachment as \( p'_1 \) and \( p'_2 \), respectively. The blood flow velocity upstream and downstream at pre-attachment are presented as \( v_1 \) and \( v_2 \), respectively, and those at post-attachment are presented as \( v'_1 \) and \( v'_2 \), respectively, and that of the shunt tube is presented as \( v_s \). The cross-sectional area of the coronary artery at the proximal and distal sites of the shunt tube are established as equal, and presented as \( A \), and that of the inner lumen of the shunt tube is presented as \( A_s \).
2.1. Pre-attachment flow

From the equation of continuity [11], the relation between flow velocity and cross-sectional area upstream and downstream is

$$v_1 = v_2$$

(1)

From Bernoulli’s theorem [11], the relation between flow velocity and pressure upstream and downstream is

$$\frac{p_1}{\rho g} + \frac{v_1^2}{2g} = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + H$$

(2)

where $\rho$ is the blood density, and $H$ is the loss of head. In this case, $H$ is caused only by friction between blood flow and coronary artery, so from Weisbach–Darcy’s formula [10], $H$ is presented as

$$H = \lambda_{fb} \frac{L}{D} \frac{v_1^2}{2g}$$

(3)

From Eqs. (1)–(3), pre-attachment flow is presented as

$$Q = Av_1 = A \sqrt{\frac{2(p_1 - p_2)}{\rho S}}$$

(4)

and

$$S = \lambda_{fb} \frac{L}{D}$$

2.2. Post-attachment flow

From the equation of continuity, relationships between $v_1'$, $v_2'$, and $v_s$ are

$$v_1' = v_2'$$

(5)

and

$$v_s = \frac{A}{A_4} v_1'$$

(6)

From Bernoulli’s theorem, the relation between flow velocity and pressure upstream and downstream is

$$\frac{p_1}{\rho g} + \frac{v_1'^2}{2g} = \frac{p_2}{\rho g} + \frac{v_2'^2}{2g} + H'$$

(7)

Neglecting the loss of head due to enlargement and diminution of duct conduit caused by the shunt tube for simplification, $H'$ is presented as

$$H' = \lambda_{fb} \frac{L}{d} \frac{v_s^2}{2g}$$

(8)

From Eqs. (5)–(8), $v_1'$ is given as

$$Q' = Av_1' = A \sqrt{\frac{2(p_1 - p_2)}{\rho S'}}$$

(9)

and

$$S' = \lambda_{fb} \frac{L}{d} \left( \frac{A}{A_4} \right)^2 = \lambda_{fb} \frac{L}{d} \left( \frac{D}{d} \right)^4$$

2.3. Flow ratio of post-attachment flow to pre-attachment flow

From Eqs. (4) and (9), the flow ratio in the case of turbulent flow is represented as follows:

$$Q^* = \sqrt{\frac{\lambda_{fb}}{\lambda_{fs}}} D^{5/2}$$

(10)

$$Q^* = \frac{Q'}{Q}$$

and

$$D^* = \frac{d}{D}$$

The coefficient of the friction loss differs in turbulent flow and laminar flow [12] (Fig. 2), and the flow ratio of post-attachment flow to pre-attachment flow is calculated separately.

In turbulent flow, the coefficient of the friction loss is presented as follows from the Blasius equation:

$$\lambda = 0.3164 \text{Re}^{-1/4}$$

(11)
the results are shown in Table 1. 

\[ Q' = \left( \frac{v_1 R}{v_1} \right)^{-1/4} R^{5} = \sqrt{\frac{1}{Q''}} \left( \frac{1}{Q'' R^2} \right)^{-1/4} R^{5} \]  

\[ Q''^2 = (Q'' R^2)^{1/4} R^{5} \]  

\[ Q' = R^{5/3} \]  

\[ \lambda = \frac{64}{\text{Re}} \]  

From Eqs. (10) and (15), the flow ratio in laminar flow is presented as follows:

\[ Q' = \sqrt{\frac{v_1 R}{v_1 R}} R^{5} = \sqrt{Q'' R^{6}} \]  

\[ Q' = R^{6} \]  

3. Results

In the case of the turbulent flow, the relationship between the flow ratio of the post-attachment flow to the pre-attachment flow and the inner diameter ratio is shown in Fig. 3 from Eq. (14). The flow ratio in turbulent flow is in proportion to the ratio of the inner diameter to the third power.

In the case of the laminar flow, the relationship between the flow ratio and the inner diameter ratio is shown as Fig. 3 from Eq. (17). The flow ratio in laminar flow is in proportion to the ratio of the inner diameter to the sixth power. At present, several companies produce intracoronary shunt tubes, and the flow ratios of actual shunt tubes provided from three companies are calculated according to Fig. 3, and the results are shown in Table 1.

4. Discussion

The present study suggests that intracoronary shunt tubes have very poor capacity for blood perfusion during OPCAB. Assuming that the blood flow is turbulent flow, the post-attachment flow decreases in proportion to the ratio of the inner diameter to the third power. Assuming that the blood flow is laminar flow, the post-attachment flow decreases in proportion to the ratio of the inner diameter even to the sixth power. Using commercial shunt tubes, coronary flow may decrease to approximately from 2 to 14% of pre-attachment flow in turbulent flow, and only less than 0.1% in laminar flow.

In this study, flow simulations were performed separately for the turbulent flow and the laminar flow. Exact behavior of the blood flow in a coronary artery and an intracoronary shunt tube should be determined by experimental investigations, but generally actual vascular blood flow behaves more like laminar flow than turbulent flow [13]. However, Cassanova and Giddens described that under physiologic conditions, blood flow remains laminar proximal (upstream) to moderate and severe stenosis but becomes turbulent distally [14]. An intracoronary shunt is always placed downstream from a stenosis lesion in a coronary artery, hence it is considered that the actual post-attachment flow can be estimated as the turbulent flow value.

The results of this study suggest that the intracoronary shunt tube has a very limited ability for blood perfusion during OPCAB. However, Dapunt et al. reported results contrary to the present study [8]. They investigated the efficacy of the intracoronary shunt tube compared with simple occlusion group in a 15-min porcine OPCAB model.
and found that intracoronary shunt insertion minimized ischemia/reperfusion injury and prevented regional left ventricular function. This result seems to be excellent, but it may be due to rich pre-attachment flow because the subject of the experiment was a juvenile porcine absent of coronary artery disease. An intracoronary shunt is always placed in a distal site from a stenosis lesion in a coronary artery, and in such cases, pre-attachment flow decreases severely or at least moderately.

Muraki et al. described regional myocardial blood flow under intracoronary shunt perfusion in detail [15]. Regional myocardial blood flow decreased to approximately 30% of the baseline value under normotension, and that decreased to approximately 10% of the baseline value under hypotension. Their results were relatively corresponded to the present study. However, their data on regional myocardial blood flow was somewhat greater than that expected by estimating coronary flow in the present study. There may be some collateral flow in vivo myocardium even if decrease of coronary artery flow occurs suddenly, and this may explain the discrepancy.

In conclusion, the coronary flow under intracoronary shunt perfusion is estimated as less than 14% of the pre-attachment flow by fluid dynamic analysis. This result suggests that the use of intracoronary shunt tubes in OPCAB may rarely contribute to maintenance of coronary flow, and they should be used carefully, especially in a jeopardized coronary artery.

Acknowledgements

We thank Tatsuya Ishiyama, MS, Division of Mechanical Science, Graduate School of Engineering, Hokkaido University, for help with theoretical analysis of fluid dynamics.

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