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The Impact of Bypass Graft Stenosis on Coronary Blood Flow

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ABSTRACT

The reduction in coronary flow caused by stenosis of the bypass graft was investigated using a mechanical model of a branching coronary artery with a graft avoiding an 80' • stenosis of one branch. The aortic pressure to dynamic pressure ratio and flow Reynolds number were matched to the biological system. For settings that mimicked rest and activity, changes in coronary flow were assessed for a range of stenosis (0-100a) of bypass grafts with graft-to-coronary-diameter ratios of 4.1, 3:1, 2:1, and 1:1. These research' findings show that: 1) In order to reduce coronary flow while at rest, bypass grafts must have significant stenosis. and when the bypass's diameter is big in comparison to the coronary artery, even moderate stenosis will now reduce after exercise; 2) For bypass grafts with the same diameter as the coronary artery, mild stenosis reduces coronary flow; and 3) a significant reduction in flow resulting from bypass graft stenosis only happens when the diameter of a stenosis in a graft is smaller than the diameter of the coronary artery.

1 Introduction:

There are currently several hundred thousand individuals with coronary artery disease who have undergone coronary artery bypass graft (CABG) procedures, and this number is still rising quickly. Following CABG surgery, coronary angiographic investigations have demonstrated that the lumen of a

CABG often experiences localized stenosis or a uniform decrease in diameter over time. However, because it is currently impractical to quantify coronary stenosis and CBF in individuals who have undergone CABG procedures, the impact of narrowing a bypass graft on CBF is unknown. To our knowledge, there has only been one extremely small study of the fluid dynamic effects of stenosis of CABGs using appropriate modelling techniques. However, the effect of bypassing a coronary artery stenosis on CBF has been studied in mechanical models, "experimental animals," and human subjects. In that study, the effects of CABGs of two different sizes on flow were measured using a single vessel with a bypass instead of a branched vessel system. The aorta, a single coronary artery, and a diagonal bypass graft were all represented by straight glass tubing. To optimize coronary flow in this simplified scenario, the bypass to coronary diameter ratio and the graft's angle of attachment to the coronary were adjusted. The beginning of turbulence and the specifics of velocity profiles were the main subjects of measurements made throughout that investigation. The impact of stenosis of CABGs (with bypass graft and branching coronary arteries) on CBF has not been adequately studied using mechanical model.

In this study, we investigated the reductions in CBF linked to bypass graft stenosis for grafts of various diameters using a suitably scaled mechanical model and dimensional analysis.

We anticipate that these investigations will be helpful in determining the hemodynamic importance of stenosis in CABGs seen by angiography.

2 Materials and Methods:

Changes in coronary flow caused by bypass graft stenosis were investigated using a scaled mechanical model of the left coronary artery circulation, which included the left main, left anterior descending, and circumflex coronary arteries as well as one bypass graft. Figure 1 schematically depicts the model's geometry. To ensure that the model accurately simulates the fluid behaviour in the living circulation, the proper no-dimensional parameters must be matched when attempting to use a mechanical model to draw conclusions about the fluid mechanics of the coronary artery system. The use of dimensional analysis ensures this matching, or dynamic similarity. For the CABGs under consideration, the main fluid variables for steady flow are the aortic pressure (p), the fluid's density (p), viscosity (p), and velocity (V), as well as the diameter (d) of the relevant coronary vessel. Other significant factors include the diameters of the bypass graft and coronary stenoses. The flow Reynolds number (pVd/p), the dimensionless pressure ratio (p,/pV'), the percentage of stenosis in each channel, and the ratio of bypass diameter to

coronary diameter are the no dimensional factors that need to be matched for steady flow, according to dimensional analysis.

For unstable (pulsatile) flow, time becomes a crucial variable. The appropriate no-dimensional variable to match is 2rpfd'/p, where f is the pulse rate. But for the issue of flow turbulence caused by a stenosis and for the bypass

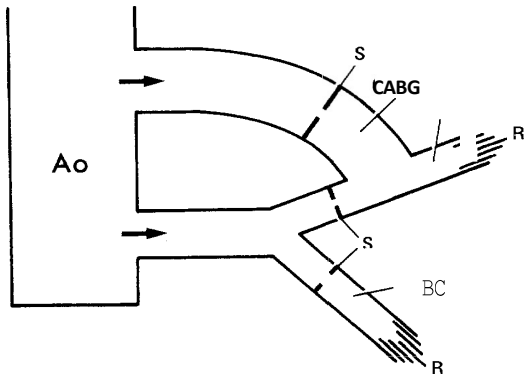


FIGURE 1. An illustration of the mechanical model for a coronary artery bypass graft (CABG) procedure. Both the unbypassed branch (40% diameter narrowing) and the bypassed branch (80% diameter narrowing) have a fixed stenosis. For bypass-to-coronary-diameter ratios of 4.1, 3:I, 2'I, and 1, the stenosis of the bypass grafts was changed from 0-l00Wo.1. The circumflex coronary artery (CIRC), the left anterior descending coronary artery (LAD), the distal coronary resistance (fi), the stenosis graft scenario (S). The scenario may be regarded as "quasi-stationary," which means that the flow at any given moment is essentially the same as a steady flow under the same instantaneous conditions, because the pulse rate is so low in comparison to the frequencies of turbulent motion. As a result, the current investigation was conducted in a consistent manner.

According to Benchimol et al.'s findings, the aortic pressure ratio (p/pV') and Reynolds number (pVd/y) in the typical human coronary circulation are roughly 80 and 300, respectively. These values were matched in our system (without stenosis) by utilizing a mixture of glycerin because our system was developed at roughly double actual size. and water, resulting in a viscosity four times greater than that of water, and by modifying the downstream resistance to produce a fluid velocity of 20 cm/sec and the reservoir pressure to 25 mm Hg. Both of the simulated coronary arteries had a diameter of 0.635 cm, or 1/4 inch. In one branch of the system, a constant diameter narrowing of 80% was circumvented by inserting stenosis of different diameters into grafts of varying diameters. There was a 40% diameter narrowing without a bypass graft in the other branch of the system.

The stenosis of 80% and 40% were chosen because the former indicates a coronary narrowing that could be circumvented, whilst the latter indicates a coronary narrowing that most likely would not. Flexible, inelastic tygon tubing was used to create coronary arteries and bypass grafts. Every stenosis was made from 1.27-cm-long plastic cylinders. A huge tube, symbolizing the aorta, was attached to the coronary arteries and bypass grafts. This tube interacted with a variable-height reservoir that was open to the atmosphere and provided a steady, regulated pressure.

A graduated cylinder was used to collect the outflow from the two coronary branches over a period of five or ten seconds. The reproducibility of measurements performed using this technique was found to be in the range of 0-9.7% (mean 4.1%) in flow measurements that were repeated for specific cases. The mechanical model was used to quantify changes in coronary flow caused by bypass graft stenosis during flow that mimicked human rest and exercise. In order to achieve flow Reynolds numbers of about 300, coronary flow at rest was mimicked by varying the resistance at the ends of the coronary arteries (without stenosis in the coronary arteries and with the bypass closed).

By lowering the resistance at the end of the coronary arteries, coronary flow during exercise was simulated and increased to about 3'/z times the flow at rest under the same conditions. After that, stenosis were fixed at a diameter narrowing of 40% in the unbypassed vessel and 80% in the bypassed vessel. Each branch's coronary outflow was measured for bypass graft diameter stenosis of 0%, 20%, 40'7, 60%, 80%, 90%, and 100%. Four distinct diameters of bypass grafts, corresponding to graft-to-coronary-diameter ratios of 4:1, 3:1, 2:1, and 1:1, were examined.

3 Results:

Table 1 shows changes in coronary flow caused by bypass graft stenosis when the resting condition was simulated. Flow measurements (Q) were normalized by dividing each value by the flow in the bypass (Q) when there was no stenosis. As a result, the amount Q/Q illustrates how a bypass graft's stenosis affects coronary flow in comparison to the flow that existed when the bypass had no stenosis.

The flow in the bypassed coronary channel was between 5.53 and 5.93 ml/sec when all four bypass grafts with graft-to-coronary-diameter ratios of 4: I–1: 1 were unobstructed. With a diameter narrowing of the bypass graft of only 40% for a bypass-to-coronary-diameter ratio of 1:1, flow in the coronary vessel with the bypass started to drop; however, it changed to 80%, 85%, and 90% for bypass-to-coronary diameter ratios of 2:1, 3:1, and 4:1, respectively (fig. 2).

Table 2 shows changes in coronary flow that were observed during exercise simulation. The flow in the coronary channel containing the bypass graft was 44.0–48.6 ml/sec when the graft-to-coronary diameter ratios of 4:1–2:1 were unobstructed. Nevertheless, coronary flow with the l:1 bypass graft was only about 27 ml/sec (by ex-trapolation). For a bypass with a graft-to-coronary-diameter ratio of 1:l, coronary flow in the channel containing the bypass graft started to decline with mild graft constriction (fig. 3). But, The flow in the coronary vessel containing the bypass graft did not start to decrease for the bypass grafts with bypass-to-coronary-diameter ratios of 2:1, 3:1, and 4:1 until the graft's diameter narrowed by 20%, 40%, and 60%. TABLE 1. Alterations iii flow due to stenosis of a Bypassed Graft in a Mechanic. Model of a Branched Coronary Artery S yalem Making a Fixed stenosis of the Unbypassed Branch (/0% Diameter Narration) and the Bypassed Branch [80% Diameter Narration]. Sifting Unobstructed Reynolds Number at 300 with Bypass Closed

Ratio of bypass diameter to vessel diameter	Diameter stenosis of bypass	Flow (ml/sec)		Normalised flow in Bypassed vessel (Q/Q),
		Bypassed vessel	Unbypassed vessel	
4:1	0	5.53	5.70	1.00
	20	5.80	5.80	1.05
	40	5.77	5.77	1.04
	60	5.80	5.80	1.05
	80	5.67	5.73	1.02
	90	5.50	5.53	0.99
	100	2.20	5.53	0.40
3:1	0	5.93	5.60	1.00
	20	5.87	5.60	0.99
	40	5.97	5.67	1.01
	60	5.93	5.67	1.00
	80	5.80	5.57	0.98
	90	4.93	5.50	0.83
	100	3.10	5.60	0.52
2:1	0	5.93	5.37	1.00
	20	5.97	5.47	1.01

	40	6.00	5.53	1.01
	60	5.83	5.60	0.98
	80	5.60	5.47	0.94
	90	4.47	5.53	0.75
	100	3.13	5.37	0.53
1:1	0	5.83	5.53	1.00
	20	5.70	5.57	0.98
	40	5.63	5.47	0.97
	60	5.00	5.53	0.86
	80	4.17	5.53	0.71
	90			—
	100	3.31	5.43	0.54

Correspondingly (fig. 3). For graft-to-coronary-diameter ratios of I:1, 2:1, 3:1, and 4:1, respectively, the steepest decline in flow happened at roughly 50%, 65'%, 80%, and 90%. When the resting state was simulated, occlusion of the bypass graft had no effect on flow in the unbypassed coronary channel (table 1), but when exercise was simulated, occlusion of the bypass graft decreased coronary flow in the unbypassed vessel by about 10-20% (table 2).

4 Conclusion :

ccurate measurements of stenosis and pressures are necessary to comprehend how a bypass graft's stenosis affects the flow in a branching coronary system.

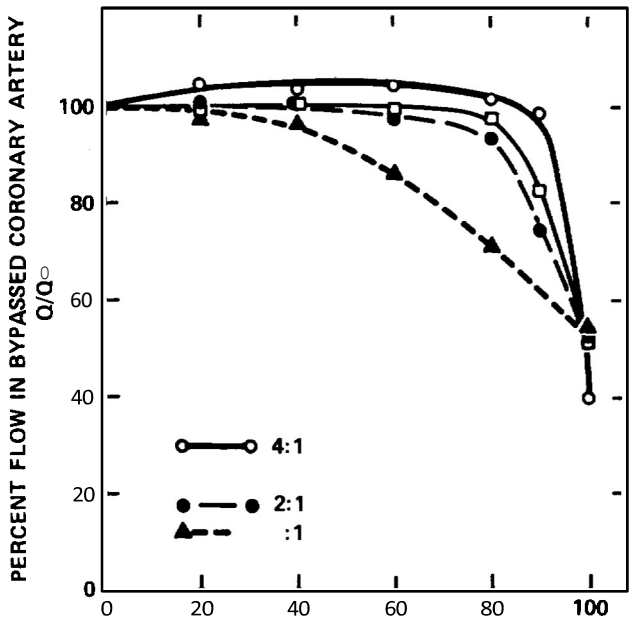
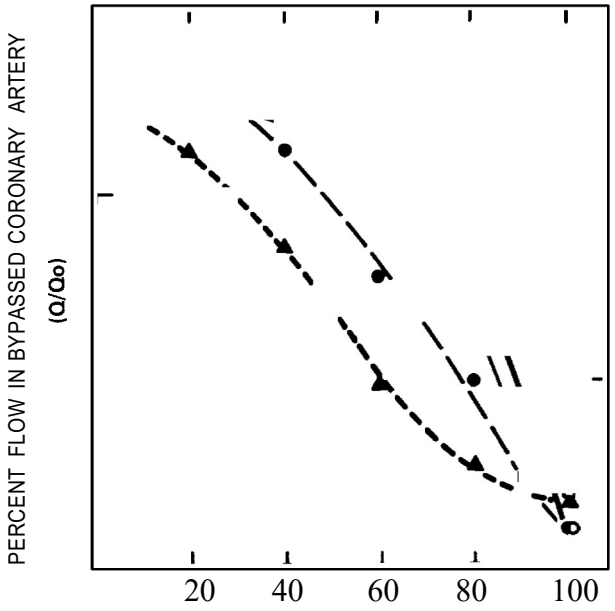


FiGURE 2. The decrease in flow in the bypassed coronary artery due to bypass graft stenosis during simulated rest, as determined in a model coronary flow system with stenosis in both branches. and flows at several locations. However, such investigations are not practical in patients undergoing myocardial revascularization due to the inevitable and essential limits of research involving human subjects.



PERCENT DIAMETER NARROWING IN BYPASS GRAFT

FIGURE 3 Normalized decrease in flow in the bypassed coronary artery due to bypass graft stenosis during exercise simulation, as assessed in a model coronary flow system with stenosis in both branches Graft in a Mechanical Model of a Branched Coronary Artery System Having a Fixed Stenosis of the Bypassed Branch (80% Diameter Narrowing) and of the Unbypassed Branch (40% Diameter Narrowing). Exercise Simulated by Setting Unobstructed Reynolds Number at Approximately 3

Ratio Bypass diameter to Vessels Diameter	Diameter of stenosis bypassed %	Bypassed vessels	Unbypassed vesels	Normlised flow in bypassed vessels Q/Q_o
4:1	0 20 40	44.4 46.4	22.2 21.6 22.4	1.0 1.05 1.02

	60 80 90 100	45.2 42.8 28.4 15.2 3.5	22.4 22.4 20.9 20.6	0.96 0.64 0.34 0.08
3.1	0 20 40 60 80 90 100	48.6 47.20 47.00 37.40 29.40 9.40 3.80	23.20 23.20 22.80 22.00 22.20 21.20 21.50	1.00 0.97 0.97 0.77 0.60 0.19 0.16
2.1	0 20 40 60 80 90 100	44.0 45.20 39.60 27.60 17.80 7.60 3.70	22.40 23.00 22.40 22.00 22.00 21.40 21.00	1.00 1.03 0.90 0.63 0.40 0.17 0.08
1.1	0 20 40 60 80 90 100	- 24.40 18.80 10.60 6.00 - 3.80	- 21.20 21.40 21.50 21.00 - 17.60	- 0.80 0.69 0.39 0.22 - 0.14

Based on an extrapolated flow value of 27.5 ml/see for diameter stenosis of the bypass (Q_O).evaluated after CABG operations. In addition, the mathematical problem of the flow in a branchedsystem of this type is an unsolved problem in fluid mechanics. A mechanical model is ideally suited for determining the relationships among pressure drop,degree of stenosis, and flow in this complex situation,because the

pertinent variables can be easily controlled and accurately measured. This method of modeling, which uses dimensional analysis,'2 is often used in engineering to solve physical problems that cannot be solved mathematically; the results of such model experiments are applicable to the livingsystem."1 Flow may be reduced by resistance due to laminar or turbulent wall shear stress and by free turbulence, which is turbulence at a jet boundary rather than at a vessel wall, as may be produced by a stenosis in any segment of a branched system. We and others4 5 have observed that there is near-stasis in the segment of the bypassed coronary vessel between its origin and the bypass graft. Therefore, flow in the portion of the bypassed coronary vessel that is distal to the stenotic bypassed graft is determined primarily by the wall shear stress in the bypass, the free turbulence generated by the stenosis in the bypass, possible turbulence at the site of anastomosis, and the distal resistance of the bypassed vessel. The onset of turbulence in a free jet from stenosis of an artery has been accurately predicted13 by the empirical expression developed from the pipe data of Johansen'0 in accordance with the equation Re = 2000 (d/D)2, where d and D represent the diameter of the stenosis and the vessel, respectively. If we apply this equation to the cases of stenosis of bypass grafts that we studied (figs. 2 and 3) and assume that flow in the bypass graft is approximately equal to the flow in the coronary vessel distal to the bypass, the onset of turbulence is to be expected at the degrees of stenosis for the resting and exercise states shown in table 3 (noting that Re = pVD/u = 50.1 Q in the bypassed coronary). These calculations are for steady flow and the present study has been restricted to steady flow experiments. It has been shown previously'3 that such experiments are matched very well by animal experiments when considering flow in stenotic vessels, provided that the flow Reynolds number and the geometric ratios are properly matched. Table 3 indicates that a turbulent jet from a stenosis is not produced in a bypass graft in the resting state for less than a 60% stenosis. The onset of turbulence occurs at greater percent diameter narrowing as the diameter of the bypass grafts becomes larger. However, the diameter of the orifice of a stenosis in the bypass graft at the onset of turbulence increases as the diameter of the bypass becomes larger. In the exercise state, for a bypass graft equal to the coronary martery, turbulence exists in the bypass even with no stenosis. This may explain why there is less flow in the 1:1 bypass graft without stenosis than in the larger grafts. A bypass graft of four times that diameter (4:1) is without turbulence until a 45% stenosis is produced. These calculations show that in all cases studied the use of a larger diameter bypass increased

TABLE 3. Percent Diameter Narrowing of Bypass Graft Needed to Produce a Turbulent Jet

Bypass diameter/ coronary diameter	At rest	During Exercise

4	80	45
3	78	37
2	73	23
1	61	0

both the percent stenosis and the orifice area of a stenosis required to produce a turbulent jet in the bypass graft. These calculations agree with the observed decreases in flow (figs. 2 and 3). In addition,

the experimental results (figs. 2 and 3) indicate that marked decreases in flow occur only when the diameter of the stenosis of a bypass graft becomes less than the diameter of the coronary artery. During simulation of the resting state, with no stenosis in the bypass, the main contribution to

resistance was in the distal portion of the bypassed vessel rather than in the bypass graft, because coronary flow was increased by the bypass graft to nearly the same levels for each of the four grafts (bypass-tocoronary-

diameter ratios of 4:1-1:1 [fig. 2]). At greater than 80-90% diameter narrowing of the bypass, the main contribution to resistance evidentally

shifted to turbulence at the stenosis of the bypass graft for the three largest grafts (bypass-to-coronarydiameter ratios of 2:1-4:1). The sharp decreases in flow with stenoses of greater than 80-90% in these three grafts are similar to the sharp decreases in flow in animals with stenosis of a single coronary vessel.17-19 The change in flow is markedly different for a bypass graft of the same diameter as the coronary, in that the reduction in flow begins with relatively mild stenosis of the bypass graft and progresses gradually. The reasons for the differences in flow through bypass grafts of large vs small diameter have not been determined. However, it is clear that for laminar flow the resistance due to wall shear stress (i.e., the pressure

drop/unit length) increases with the fourth power of the diameter so that the resistance due to a 1:1 bypass graft without stenosis is 15 times as large as that of a bypass graft of twice (2:1) the diameter.20 Bypass grafts having relatively large diameters and low wall shear stress (bypass-to-coronary-diameter ratios of 4:1-2: 1) require a high grade (greater than 80-90%) stenosis of the bypass before turbulence at the stenosis begins to decrease flow in the graft. Because resistance to flow due to wall shear stress is

much more marked for the smallest diameter bypass graft that we studied, the effect on flow of the added resistance due to free

turbulence at a stenosis of this graft produced a gradual decrease in flow.

During the relatively high flow of simulated exercise, resistance due to turbulence becomes more important than laminar shear stress, because turbulent shear stress is proportional to the square of flow while laminar shear stress is directly proportional to flow.2' As a result, reduction in coronary flow with simulated exercise began with much smaller stenoses of bypass grafts than was observed when the resting state was simulated (figs. 2 and 3). The main contribution to resistance, with no stenosis of the bypass, remained at the distal end of the bypassed coronary vessel for the

three largest bypass grafts (bypass-to-coronarydiameter ratios of 4:1-2: 1), because coronary flow was nearly the same for these bypass grafts (table 2). However, the bypass graft that was of the same diameter as the coronary artery reduced maximal flow to almost one-half that measured in the relatively large bypass grafts. In the smallest graft, the main contribution to increased resistance during exercise appeared to be due to turbulence along the length of the bypass graft. The effect of the additional resistance due to the turbulent jet produced by a graft stenosis was therefore less evident when the high flow of exercise was simulated, and flow dropped gradually as stenosis of the graft increased. It is difficult to know how accurately our mechanical model simulated coronary flow during exercise. Increases in coronary flow of 3-7 times the values measured at rest have been shown during maximal coronary arterial dilatation in experimental animals,22 26 while maximal increases of approximately 1 l/4-3 times baseline coronary flow values have been measured through bypass grafts intraoperatively in human subjects after release of an occluded bypass graft.6- 10 The reasons for the differences in maximal coronary flow in these two situations have not been determined. However, the percent decrease in coronary flow due to stenosis of a bypass graft is related to the flow Reynolds number in the system, with decreases in flow occurring with less diameter narrowing of a bypass and more gradually as the flow Reynolds number in the system increases. We conclude from these studies that: 1) marked stenosis of bypass grafts is needed to decrease coronary flow in the resting state when the diameter of the bypass is large relative to the coronary artery; 2) even moderate stenosis of relatively large bypass grafts will decrease coronary flow during the high flow of exercise; 3) for bypass grafts of the same diameter as the coronary artery, coronary flow is decreased with mild stenosis at rest and flow is less than maximal even when unobstructed during exercise; and 4) a marked decrease in flow due to stenosis of a bypass graft occurs only when the diameter of a stenosis in a graft is less than the diameter of the coronary artery.

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