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# Graft design strategies with optimum antegrade bypass flow in total arterial off-pump coronary artery bypass

Hiroyuki Nakajima *, Junjiro Kobayashi, Osamu Tagusari, Kazuo Niwaya, Toshihiro Funatsu, Alaa Brik, Toshikatsu Yagihara, Soichiro Kitamura

*Department of Cardiovascular Surgery, National Cardiovascular Center, 5-7-1 Fujishirodai, Suita, Osaka 565-8565, Japan*

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**Abstract**

**Objective:** In arterial conduits, graft flow is one of the major determinants of long-term patency. We sought to delineate the effect of strategy for graft arrangement and design to three-vessel disease by evaluation of the dominant flow direction in each segment of a bypass graft. **Materials and methods:** We reviewed coronary angiograms of 1571 bypass grafts in 395 patients who underwent total arterial off-pump coronary revascularization without aortic manipulation for three-vessel disease since December 2000. The graft flow graded as A (antegrade), B (competitive), C (reverse), and O (no flow = occlusion). The current arrangement and design has been introduced since March 2003, and consists of the in-situ left internal thoracic artery (ITA) to the anterior descending artery and the composite I-graft of the right ITA and radial artery to the left circumflex (LCX) and right coronary artery (RCA) territories. Either clockwise or counterclockwise orientation, the I-graft was chosen to achieve a sufficient antegrade flow. Group I consisted of 181 patients with a single in-situ ITA as a composite Y-graft. Group II consisted of 214 patients with bilateral in-situ ITAs, which subdivided into Subgroup II-A consisted of 80 patients with bilateral in-situ ITAs until February 2003, and Subgroup II-B consisted of 134 patients with bilateral in-situ ITAs since March 2003. **Results:** The number of distal anastomoses was $3.52 \pm 0.63$ in Group I, and $4.36 \pm 0.83$ in Group II, respectively ($p < 0.0001$). The overall graft patency rate was 98.6% (1549/1571), and there was no significance different between the groups. The rate of grade A in Group II was 863/933 (92.5%) and was significantly higher ($p = 0.049$) than that of Group I 572/638 (89.7%). The rate of functioning bypass in Subgroup II-B was (95.8%) 568/593, and was significantly higher ($p = 0.03$) than that in Subgroup II-A (92.4%) 314/340. In Subgroup II-B, 233/268 (86.9%) of the conduits had completely grade A bypass flow, and this ratio was significantly higher ($p = 0.04$) than that in Subgroup II-A (79.4%) 127/160. **Conclusion:** Usage of bilateral ITAs and selecting the orientation of the I-graft to LCX and RCA branches provide maximal distal anastomotic sites with satisfactory graft patency rate, and simultaneously minimized the incidence of reverse and competitive flow.



*Keywords:* Off-pump; CABG; Arterial graft; Angiography

## 1. Introduction

Coronary artery revascularization was first performed on beating hearts [1]. Off-pump CABG combined with a no-aortic-touch technique has been accepted as an effective procedure to avoid the neurologic and aortic complications, and to reduce the operative risk. A composite graft using in-situ and free grafts is necessary for complete revascularization in patients with multi-vessels disease, and the arterial graft is commonly used because of its beneficial characteristics in terms of expectancy of both graft patency and improved late outcome [2].

In the arterial graft, circumstances of the blood flow in the graft lumen may be an important determinant for the durable patency. It has been reported that occlusion or string sign in the arterial graft is closely correlated with the insufficiency of the bypass flow, which represents competitive and reverse flow. It can occur either when the pressure capacity of the bypass graft is not enough; or the intraluminal pressure in the native coronary artery is relatively high due to the moderate stenosis of the native coronary artery. The previous study showed that reverse flow in the non-individual conduit had a significant correlation with the presence of moderately stenotic right coronary artery (RCA) and more than four target coronary branches for a single in-situ internal thoracic artery (ITA) [3]. In addition, the management of a coronary branch with critical stenosis and the strategy for the graft arrangement play essential roles for blood flow distribution [4].

The objectives of this study were (1) to compare the bypass flow in different bypass graft configurations for complete revascularization of the three-vessel territories

* Corresponding author. Tel.: +81 6 6833 5012; fax: +81 6 6872 7486.
*E-mail address:* hnakajim@hsp.ncvc.go.jp (H. Nakajima).

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using the flow grading system and (2) to evaluate the different strategy for graft arrangement and design.

## 2. Materials and methods

### 2.1. Study population

Between December 2000 and June 2005, 395 consecutive patients (male; 321, female; 74, mean age; 66.1 ± 9.1 years) underwent off-pump complete revascularization for three-vessel disease with arterial grafts (Table 1). Patients were excluded if they (i) had a bypass graft of the in-situ gastroepiploic artery or the saphenous vein, (ii) had individual grafts only, or (iii) did not undergo postoperative coronary angiography.

All patients underwent pre- and 2-week postoperative coronary angiographies, which were evaluated by the cardiologist for the native coronary artery stenosis and the graft patency, respectively.

The evaluation of graft patency is based on the concept of flow grading system (Table 2). A patent graft meant that the graft had a complete continuity of the graft lumen in the overall length from the subclavian artery to the target coronary branch, irrespective of the flow direction.

Grade O; (occlusion) was defined as the continuity of the graft lumen was interrupted at any level until the target coronary branch.

Grade A; means that antegrade graft flow was found in most of the multi-plane ITA angiography. Grade B; (competitive flow) defined as a situation in which the target vessel was slightly opacified from the ITA injection, and the bypass graft did fill by retrograde flow from the native coronary artery injection. Grade C; (reverse flow) the distal anastomotic sit was not opacified from the ITA graft injection at all, but it did fill clearly by retrograde flow from the native coronary artery injection. Flow grade was recorded for each target coronary branch. Any bypass graft graded as occluded or having reverse flow was considered not functioning because it did not contribute to coronary perfusion and relief of ischemia in the target region. A patent bypass without reverse flow was graded as functioning, and the rate of functioning grafts was defined as the proportion of functioning bypass grafts to the total number of bypass grafts. The definition of terms used in the present study is as follow. The in-situ ITA graft is an ITA, which was divided only at its distal portion. A composite graft is a bypass conduit consisting of one in-situ graft and a free graft anastomosed to it (in an end to end, end to side, or side to side fashion). An individual bypass was defined as a bypass conduit having one distal anastomoses and one in-situ graft. This included the straight composite grafts; i.e. I-graft, to one target coronary branch. A bypass conduit having two or more distal anastomosis, such as a sequential, Y-, or K-graft, was defined as non-individual.

Table 1
Baseline characteristics

| | Group I (single ITA) | Group II (bilateral ITAs) | $p$ value, Group S versus B |
|---|---|---|---|
| No. of patients | 181 | 214 | |
| Age (years) | 70.3 ± 7.3 | 62.5 ± 9.0 | <0.0001 |
| Male/female | 140/41 | 181/33 | 0.07 |
| Hypertension | 106 (59%) | 108 (50%) | 0.11 |
| Hyperlipidemia | 89 (49%) | 117(55%) | 0.28 |
| Diabetes | 76 (42%) | 84 (39%) | 0.58 |
| End-diastolic volume index of LV (ml/m$^2$) | 84.4 ± 23.8 | 89.4 ± 33.3 | <0.0001 |
| Ejection fraction of LV (%) | 48.0 ± 10.8 | 46.0 ± 12.9 | 0.005 |
| Total distal anastomoses | 638 | 933 | |
| Bypass conduits used | | | |
| Individual (target banch = 1) | 0 | 142 | |
| Non-individual (target branches>2) | 181 | 286 | |
| In situ ITA sequential | 0 | 36 | |
| Composite Y-graft | 160 | 88 | |
| Composite K-graft | 21 | 15 | |
| Composite I-graft | 0 | 147 | |
| Total | 181 | 428 | |

ITA; internal thoracic artery LV; left ventricle.

Table 2
Concept of flow grading

| | Flow grade | | | |
|---|---|---|---|---|
| | A | B | C | O |
| Flow direction | Antegrade | Competitive | Reverse | No-flow |
| Patency | Patent | Patent | Patent | Occluded |
| Function | Functioning | Functioning | Non-function | Non-function |
| Durability | Yes | No | No | No |

Table 3
Baseline characteristics

| | Subgroup II-A (~Feb. 2003) | Subgroup II-B (Mar. 2003~) | *p* value, Group B-1 versus B-2 |
|---|---|---|---|
| No. of patients | 80 | 134 | |
| Age (years) | 60.6 ± 8.2 | 63.6 ± 9.4 | 0.02 |
| Male/Female | 68/12 | 113/21 | 0.90 |
| Hypertension | 43 (54%) | 65 (49%) | 0.46 |
| Hyperlipidemia | 49 (61%) | 68(51%) | 0.14 |
| Diabetes | 32 (40%) | 52 (39%) | 0.86 |
| End-diastolic volume index of LV (ml/m$^2$) | 92.9 ± 35.1 | 87.7 ± 32.0 | 0.27 |
| Ejection fraction of LV (%) | 46.5 ± 13.9 | 45.6 ± 12.2 | 0.67 |
| Total distal anastomoses | 340 | 593 | |
| Bypass conduits used | 160 (100%) | 268 (100%) | |
| Individual (target banch = 1) | 44 (27.5%) | 98 (36.6%) | 0.053 |
| In situ ITA | 27 (16.9%) | 93 (34.7%) | <0.0001 |
| Composite I-graft | 17 (10.6%) | 5 (1.9%) | <0.0001 |
| Non-individual (target branches >1) | 116(72.5%) | 170 (63.4%) | 0.053 |
| In situ ITA sequential | 10 (6.3%) | 26 (9.7%) | 0.21 |
| Composite Y-graft | 49 (30.6%) | 39 (14.6%) | <0.0001 |
| Composite K-graft | 13(8.1%) | 2 (0.7%) | <0.0001 |
| Composite I-graft | 44 (27.5%) | 103 (38.4%) | 0.02 |
| ITA-RA-LCX-RCA (clockwise) | 0 | 67 (25.0%) | <0.0001 |
| ITA-RA-RCA-LCX (counterclockwise) | 44 (27.5%) | 36 (13.4%) | 0.0003 |

ITA; internal thoracic artery LV; left ventricle LCX; left circumflex artery RA; radial artery RCA; right coronary artery.

The design and arrangement of the bypass conduits were primarily determined by the operative risk and special relationship of the target sites (Tables 1 and 3). Group I consisted of 181 patients with single in situ ITA graft as Y- or K- graft. In Group II, 214 patients had bilateral in situ ITA in the combination of individual, Y-, K- or I-graft. Group II was divided into two subgroups by the date of surgery, because the current standard strategy has been introduced in March 2003, aiming at preventing high-risk situations of reverse and competitive flow [4]. Subgroup II-A consisted of 80 patients until February 2003, and Subgroup II-B consisted of 133 patients between March 2003 and June 2005 (Table 3). In the standard technique in Subgroup II-B, one in-situ ITA, usually the left, supplies to the left anterior descending artery (LAD) territory and an I-graft of the contra lateral ITA, usually the right, and the radial artery to the circumflex (LCX) and the right coronary artery (RCA) in a clockwise orientation, which meant a side to side anastomosis with the LCX branch and an end to side anastomosis to the RCA branch (Fig. 1). The counter-clockwise orientation was occasionally chosen to avoid grafting to the RCA branch with 75% stenosis at the end of the conduit, because reverse flow is commonly found at the distal end of the conduit [4]. In Subgroup II-A, the I-graft was used only in a counterclockwise orientation for the safety of redo operation in the future (Table 3). When the bypass conduits had grade A bypass flow to all target coronary branches, we considered that the design of the bypass conduit was successful.

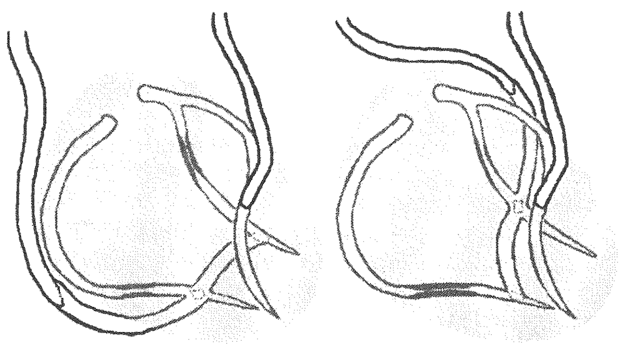

Fig. 1. A composite I-graft in the clockwise (right) and counterclockwise orientation (left).

Through a standard median sternotomy, the pericardial cavity was widely opened and deep pericardial sutures were placed for traction. Heparin was administered and activated coagulation time was maintained at more than 300 s until completion of anastomosis. In the present study, the ITA was harvested using either conventional (combined with vein and fascia), or semiskeletonized (partially combined with vein), or skeletonized technique [5]. All the distal portion of ITA grafts were larger than 1.5 mm in diameter assessed by insertion of 1.5 mm flexible probe. Allen's test was routinely performed before harvesting the radial artery and capillary refilling of the palm within 10 s was judged as negative [6]. Irrespectively to patient's age, the radial artery of non-dominant forearm was harvested by using an ultrasonic scalpel, treated with a papaverin hydrochloride solution [7], and was divided into two pieces when necessary. In the side-to-side anastomosis, a longitudinal arteriotomy of 6–10 mm was performed on both native coronary artery and arterial graft, and it was long enough for anastomosis without turbulence. The angle of the graft placement was adjusted to 0–90 degree to save the length and avoid kinking.

The distal anastomoses were carried out while stabilizing the coronary vessels using Octopus II+ or III stabilizer (Medtronic, Minneapolis, MN) and a retract-O-tape (Quest Medical, Inc., Allen, TX) was placed for temporary proximal occlusion. The surgical field was maintained by $CO_2$ blower and an intracoronary shunt; Anastflo (Edwards Lifesciences, Irvine, CA) for coronary artery of 1.5 and 2.0 mm in diameter, Clearview (Medtronic, Minneapolis, MN) for coronary artery 1.25 and 1.0 mm in diameter, was used.

Continuous infusion of diltiazem was started during the operation and continued until oral medication was started, usually on the first postoperative day. It was terminated and replaced by nicardipine hydrochloride if sufficient heart rate could not be obtained. In the intensive care unit, heparin was administrated continuously for 24 h, and replaced by oral administration of aspirin.

### 2.2. Statistical analysis

The continuous variables are expressed as mean ± stan-standard deviation, and compared by the unpaired Student's *t*-test between the two groups. The data of two independent groups were compared by Fisher's exact probability test. The differences in the outcomes were considered statistically significant at a probability value <0.05.

## 3. Results

The over graft patency rate was 98.6% (1549/1571). The number of distal anastomoses in Group II was 4.36 ± 0.83, and it was significantly greater than in Group I (3.52 ± 0.63) ($p < 0.0001$) (Table 2). In Group I, 572 (89.7%) bypass were grade A, whereas 20 (3.1%), 36 (5.6%), and 10 (1.6%) were grade B, C and O, respectively. The graft patency rate in Group II was 98.7% (921/933), and was comparable with that in Group I (98.4%) (628/638). However, the rate of grade A bypass flow in Group II was 92.5% (863/933), and was significantly higher than that of in Group I (89.7%) (572/638) ($p = 0.049$). In Group I, the number of bypass conduits of grade A bypass flow to all target coronary branches was 122/181 (67.4%), and was significantly less than that in Group II (360/428) (84.1%) ($p < 0.0001$) (Table 4).

In the comparison of Subgroup II-A to Subgroup II-B, there was no significant difference in the graft patency rate (Table 5). However, the functioning rate in Subgroup II-B was (95.8%) (568/593) and was significantly higher than that in Subgroup II-A (92.4%) (314/340) ($p = 0.03$). In Subgroup II-B, the number of bypass conduits with the grade A bypass flow to all target coronary branches was (233/268) (86.9%), and was significantly higher than that in Subgroup II-A (127/160) (79.4%) ($p = 0.04$) (Fig. 2).

Table 4
Angiographic results

| | Group I (single ITA) | Group II (bilateral IT As) | p value |
|---|---|---|---|
| No. of patients | 181 | 214 | |
| Distal anastomoses | 3.52 ± 0.63 | 4.36 ± 0.83 | <0.0001 |
| Flow grade | | | |
| A | 572 (89.7%) | 863 (92.5%) | |
| B | 20(3.1%) | 19(2.0%) | |
| C | 36 (5.6%) | 39 (4.2%) | |
| O | 10(1.6%) | 12(1.3%) | |
| Total | 638 | 933 | |
| Antegrade flow rate | | | |
| A | 572 (89.7%) | 863 (92.5%) | 0.049 |
| Functioning rate | | | |
| A + B | 592(92.8%) | 882 (94.5%) | 0.16 |
| Patency rate | | | |
| A + B + C | 628 (98.4%) | 921 (98.7%) | 0.64 |
| Bypass conduits | 181 | 428 | |
| Flow grade in the bypass conduits | | | |
| A only | 122 (67.4%) | 360(84.1%) | <0.0001 |
| Non-A (+) | 59 (32.6%) | 68 (15.9%) | |

ITA; internal thoracic artery LV; left ventricle non-A; grade B, C, or O.

Table 5
Angiographic results

| | Subgroup II-A (~Feb. 2003) | Subgroup II-B (Mar. 2003~) | p value |
|---|---|---|---|
| No. of patients | 80 | 134 | |
| Distal anastomoses | 4.25 ± 0.83 | 4.42 ± 0.83 | 0.07 |
| Flow grade | | | |
| A | 307 (90.3%) | 556 (93.8%) | |
| B | 7(2.1%) | 12 (2.0%) | |
| C | 19 (5.6%) | 20 (3.4%) | |
| O | 7(2.1%) | 5 (0.8%) | |
| Total | 340 | 593 | |
| Antegrade flow rate | | | |
| A | 307 (90.3%) | 556 (93.8%) | 0.05 |
| Functioning rate | | | |
| A + B | 314(92.4%) | 568 (95.8%) | 0.03 |
| Patency rate | | | |
| A + B + C | 333 (97.9%) | 588 (99.2%) | 0.11 |
| Bypass conduits | 160 | 268 | |
| Flow grade in the bypass conduits | | | |
| A only | 127 (79.4%) | 233 (86.9%) | 0.04 |
| Non-A (+) | 33 (20.6%) | 35 (13.1%) | |

IT A; internal thoracic artery LV; left ventricle non-A; grade B, C, or O.

The characteristics of the native coronary branches according to anatomical location and the grade of coronary stenosis, LAD and diagonal had 92.9 and 95.9% grade A from the total number of anastomoses, respectively. The grade A flow of the graft performed for 91–100% stenosis of native coronary branches was 98.8%, while in 76–90% coronary stenosis the grafts had grade A flow in 92.9% and when the grade of coronary stenosis is 51–75%, the graft grade A was 86.0% (Table 6).

## 4. Discussion

Avoidance of cardiopulmonary bypass and manipulation of the aorta can decrease the incidence of preoperative complications. In this aorta no-touch technique, the usage of the in-situ ITA graft is almost essential and it provides a favorable long-term survival with an excellent graft patency because it has a lower incidence of atherosclerotic graft disease than the saphenous vine graft [2,8]. In previous reports, the early and midterm graft patency rates of the radial artery were equivalent to those of the ITA [9–11]. The radial artery in the composite graft may provide a better durability than that proximally anastomosed to the ascending aorta because the exposure to an excessive pressure of the aorta and wall stress and the mismatch of the wall thickness can be avoided [11,12].

On planning the configuration and design of the arterial grafts in off-pump CABG without aortic manipulation, consciousness for the anticipated direction of bypass flow

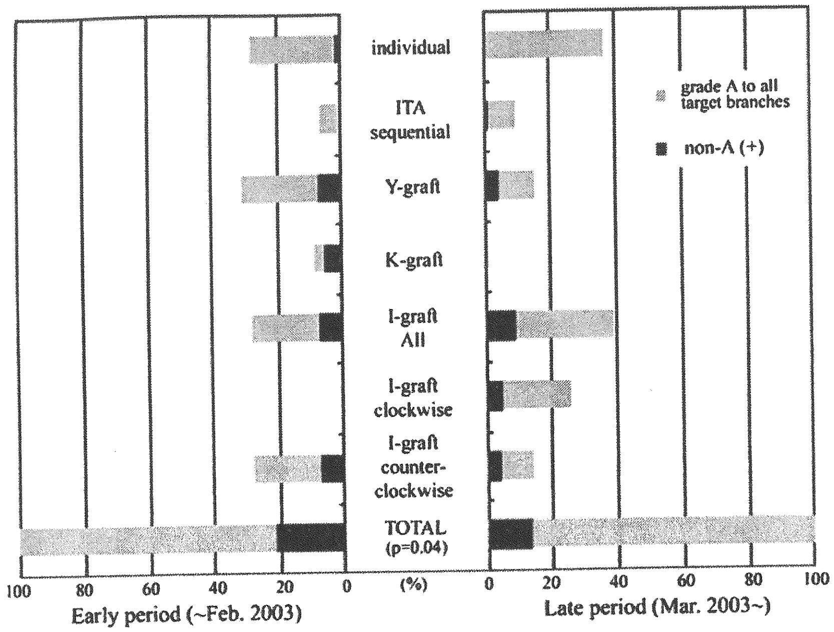


Fig. 2. Comparison of the proportion of bypass conduits used in the early and the late periods, and the rate of the conduits having only grade A, in various configurations.

may be mandatory. It was reported previously that reverse flow in the non-individual graft have significant correlations with the moderately stenotic RCA and the number of distal anastomotic sites of the composite graft [3]. Interaction of the coronary branches, which were connected to each other by a sequential or composite graft, and management of the coronary branches with moderate and severe stenoses play crucial roles in the occurrence of competitive and reveres flow. On the contrary, the graft material and size of the target branch does not correlate with the direction of bypass flow [4]. Additionaly, the patency rate of the graft with sufficient antegrade bypass flow was significantly higher than those of the graft presenting reverse and competitive flow, and the bypass grafts graded B or C were prone to close the graft lumen in the intermediate term [13,14]. It is generally believed that the long-term graft patency can be highly expected whenever arterial materials are exclusively used. However, the arterial graft without a sufficient antegrade flow has no obvious advantage regarding the long-term patency rate, as compared with the venous graft. A composite graft allows total arterial revascularization with an excellent graft patency rate and a lower incidence of cardiac events, especially for patient with atherosclerosis of the ascending aorta [15,16]. Although different arrangements and designs of the in-situ and free arterial grafts have already been reported [8,17], no optimal strategy for graft arrangement has been established yet. The decision of the configuration actually depends on the surgeon's preference or the custom of each group.

FitzGibbon et al. examined the venous conduits angiographically using the grading system of the luminal size at the narrowest portion, and the intimal irregularity as well. [18,19]. This grading system predicted the late atherosclerotic graft occlusion, which is considered as a major determinant of the long-term patency of the venous grafts. However, in the ITA graft, atherosclerosis hardly developed [20,21]. Additionally, the luminal size of the anastomotic site is not precisely measurable in the sequential fashion,

Table 6
Early angiographic results

| Characteristics of coronary branches | Number of anastomoses | Grade | | | |
|---|---|---|---|---|---|
| | | A (%) | B (%) | C (%) | O (%) |
| Location | | | | | |
| LAD main trunk | 397 | 369 (92.9) | 14 (3.5) | 10 (2.5) | 4 (1.0) |
| Diagonal | 196 | 188 (95.9) | 2 (1.0) | 5 (2.6) | 1 (0.5) |
| LCX | 461 | 424 (92.0) | 6 (1.3) | 26 (5.6) | 5(1.1) |
| RCA | 517 | 454 (87.8) | 17 (3.3) | 34 (6.6) | 12 (2.3) |
| Stenosis (%) | | | | | |
| 51–75 | 727 | 625 (86.0) | 31 (4.3) | 61 (8.4) | 10 (1.4) |
| 76–90 | 410 | 381 (92.9) | 8 (2.0) | 14 (3.4) | 7 (1.7) |
| 91–100 | 434 | 429 (98.8) | 0 | 0 | 5 (1.2) |
| Overall | 1571 | 1435 (91.3) | 39 (2.5) | 75 (4.8) | 22 (1.4) |

LAD; left anterior discending artery, LCX; left circumflex artery, RCA; right coronary artery.

especially when the angle of the graft and coronary branch is near to 90 degrees, or when the contrast medium dose fills only incompletely due to mixture with the blood flow from the native coronary artery. Furthermore, although inadequate surgical maneuvers during the operation strongly affect the luminal size by unsuccessful anastomosis or graft kinking, regression of the stenosis and the increase or growth of the diameter were relatively common finding in the arterial grafts [22]. Thus, we consider that the angiographic luminal size or graft patency may be not relevant for pure comparison of graft arrangement and design of the arterial conduits.

In the present study, the configuration and design of the arterial graft were compared not only by classifying the anatomical patency or occlusion, but also by the dominant flow direction in the arterial composite and sequential grafts. Although there was no significant difference in the graft patency rate among the groups, the use of bilateral ITAs enabled more distal anastomosis with reduced competitive and reverse flow. We considered that the appropriate pressure slope in each segment of the bypass conduit should be higher at the proximal than that at the end of the conduit to achieve an antegrade flow. The anastomosis of the bypass conduit end with a moderately stenotic coronary branch is unfavorable in most cases. Thus, the composite I-graft is useful because the target coronary branch at the end of the conduit can be chosen by determining its orientation. In the composite Y-graft, the adequate pressure slope to the both ends should be made and the indication for Y or K graft should be more carefully decided. On the other hand, the Y-graft has an advantageous in terms of increased flow capacity [23] and availability to the distant target branches, as compared with the I-graft. For the diagonal, LCX, and RCA branches, the Y- or K-graft is preferred when all target branches have severe stenosis, target diagonal branch is located at the anteroapical portion, or remarkable cardiomegaly exists. Also, selection of suitable candidates for this procedure is a major concern.

Since the bypass grafts with reverse flow do not contribute to the coronary perfusion in the grafted territory, the efficacy of CABG may be unpromising, even when the bypass graft is anatomically patent. When non-functioning or occluded graft is highly predicted at early period, an alternative therapeutic strategy should be considered such as hybrid therapy with drug eluting stent implantation for conservation of the arterial grafts for the future redo operation.

In previous study, sequential anastomoses with more than two moderately stenotic coronary branches including one at the end of the conduit were highly associated with flow insufficiency and late occlusion. Although the gastroepiploic artery is an option of choice for the RCA and LCX territories, it is unsuitable for moderately stenotic coronary branch because its pressure potential is inferior to that of the in-situ ITA [24,25].

This study has some limitations as it is not randomized. Peripheral vascular resistance in the myocardial tissue also has an important role in the coronary perfusion. Grade B flow probably includes insufficient graft flows due to both strength of the native coronary flow and poor vascularity with high resistance in the severely impaired myocardium. Although no bypass graft may be required for the latter, we could not predict the insufficient antegrade flow caused by the critically damage vasculature.

## 5. Conclusion

The use of bilateral ITAs significantly increased the bypass grafts with sufficient antegrade flow, and the I-graft to LCX and RCA branches with avoidance of anastomosis with moderately stenotic coronary branch at the end of the graft was effective for reduction of reverse and competitive flow by selecting its orientation. Flow consciousness in the graft arrangement and design may be a major concern to confirm the advantage of the arterial material and complete revascularization when the arterial grafts are exclusively used.

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