The application of intraoperative transit time flow measurement to accurately assess anastomotic quality in sequential vein grafting

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Abstract

OBJECTIVES: Intraoperative transit time flow measurement (TTFM) is widely used to assess anastomotic quality in coronary artery bypass grafting (CABG). However, in sequential vein grafting, the flow characteristics collected by the conventional TTFM method are usually associated with total graft flow and might not accurately indicate the quality of every distal anastomosis in a sequential graft. The purpose of our study was to examine a new TTFM method that could assess the quality of each distal anastomosis in a sequential graft more reliably than the conventional TTFM approach.

METHODS: Two TTFM methods were tested in 84 patients who underwent sequential saphenous off-pump CABG in Beijing An Zhen Hospital between April and August 2012. In the conventional TTFM method, normal blood flow in the sequential graft was maintained during the measurement, and the flow probe was placed a few centimetres above the anastomosis to be evaluated. In the new method, blood flow in the sequential graft was temporarily reduced during the measurement by placing an atraumatic bulldog clamp at the graft a few centimetres distal to the anastomosis to be evaluated, while the position of the flow probe remained the same as in the conventional method. This new TTFM method was named the flow reduction TTFM. Graft flow parameters measured by both methods were compared.

RESULTS: Compared with the conventional TTFM, the flow reduction TTFM resulted in significantly lower mean graft blood flow ($P < 0.05$); in contrast, yielded significantly higher pulsatility index ($P < 0.05$). Diastolic filling was not significantly different between the two methods and was $>50\%$ in both cases. Interestingly, the flow reduction TTFM identified two defective middle distal anastomoses that the conventional TTFM failed to detect. Graft flows near the defective distal anastomoses were improved substantially after revision.

CONCLUSIONS: In this study, we found that temporary reduction of graft flow during TTFM seemed to enhance the sensitivity of TTFM to less-than-critical anastomotic defects in a sequential graft and to improve the overall accuracy of the intraoperative assessment of anastomotic quality in sequential vein grafting.

Keywords: Sequential saphenous coronary artery bypass grafting • Transit time flow measurement • Anastomotic quality

INTRODUCTION

The incidence rate of coronary artery atherosclerosis remains high, and the demand for coronary artery bypass grafting (CABG) is continuously rising [1–4]. Sequential saphenous CABG has been shown to have the following advantages: fewer proximal anastomoses, less aortic damage, shorter operation duration and better patient long-term outcomes [5, 6]. The quality of each anastomosis is crucial for the long-term success of sequential saphenous CABG.

Intraoperative transit time flow measurement (TTFM) has been widely used to evaluate graft patency in CABG [7–11]. Compared with other methods for graft blood flow measurement, intraoperative TTFM is non-invasive, easy to use, reproducible, and provides real-time information about the haemodynamic characteristics of constructed grafts [12]. A number of studies have

demonstrated that intraoperative TTFM can be used to assess early graft function and to predict graft error in CABG, thus allowing for prompt revision of anastomotic imperfection and prevent graft failure [13–16]. Intraoperative TTFM has also been used to examine the haemodynamics of total graft blood flow in sequential vein grafts [11, 17]. Nordgaard *et al.* [11] and Kim *et al.* [17] used intraoperative TTFM to compare the haemodynamic characteristics of blood flow between sequential vein grafting and individual grafting and found that the total blood flow in sequential vein grafts is significantly higher than that in a single vein graft. Because of the complex haemodynamic characteristics of blood flow in a sequential graft and the complexity of coronary artery branching, the flow characteristics associated with total graft flow in a sequential graft might not accurately indicate the quality of each distal anastomosis in the sequential graft. Due to high graft blood flow in a sequential graft, a less-than-critical anastomotic defect

might not significantly reduce the total graft flow in the sequential graft, and thus, might not be detected by TTFM. In this study, we found that a temporary reduction of graft blood flow in a sequential graft during TTFM seemed to enhance the sensitivity of TTFM to anastomotic defects and to improve the accuracy of intraoperative assessment of anastomotic quality in sequential vein CABG.

MATERIALS AND METHODS

Patients

Informed consent was obtained from patients and their families. Data were collected with approval from the Institutional Ethics Committee of Beijing An Zhen Hospital. Eighty-four patients who underwent off-pump CABG in Beijing An Zhen Hospital between April and August 2012 were included in this study. All patients, including 69 men and 15 women, were operated on by the same surgeon (Dr Cheng-Xiong Gu). The age of the patients was between 46 and 82, and the average age was 62 ± 9 . The patients had the following medical histories: 47 (55.9%) cases had pre-operative hypertension; 27 (32%) had diabetes; 6 (7.1%) had previous percutaneous transluminal coronary angioplasty; 62 (70.2%) had myocardial infarction; 5 (5.9%) had cerebrovascular disease; 8 (9.5%) had respiratory disease and 3 (3.5%) had renal insufficiency. All patients had symptoms of angina before the operation. Coronary angiography revealed that all patients had triple-vessel lesions. Echocardiography showed that the average ejection fraction was $60 \pm 8\%$. Other clinical characteristics of the patients are displayed in Table 1.

Methods

Surgical technique. All patients received total intravenous anaesthesia for the operation. The patient's heart was approached through a median sternotomy. The left internal mammary artery (LIMA) and the great saphenous vein were harvested according to the routine procedure and stored in heparin solution. A heart stabilizer (Recovery Co., Ltd., Beijing, China) was used to immobilize the vessel site selected for grafting during the operation. To maintain a clear operative field, the area for grafting was washed with warm saline. The LIMA was always grafted to the

left anterior descending artery, and the great saphenous vein was grafted to other target vessels sequentially. All LIMA and vein anastomoses were sutured with a 8-0 Prolene.

Transit time flow measurement. Flow measurement was performed using a transit time flow metre (MediStim VeriQ System, Norway) after all anastomoses were completed and haemodynamic parameters, such as blood pressure and heart rate, became stable. Based on graft diameter, either 3 or 4 mm, a flow probe was used for flow measurement. Flow parameters recorded in this study included mean graft flow, pulsatility index (PI) and diastolic filling (DF). The flow parameters were recorded after waveform of graft flow and values became stable. Two TTFM methods were examined in this study, the conventional method for TTFM and a new method for the measurement. Every anastomosis of sequential vein grafts was evaluated by both methods. In the conventional method, normal graft blood flow was maintained during the measurement, and the flow probe was placed 2 cm above the anastomosis to be evaluated (target anastomosis). In the new measurement method, except the aortic proximal anastomosis and the most distal anastomosis, the remaining anastomoses in a sequential graft were evaluated by placing an atraumatic bulldog clamp a few centimetre distal to a target anastomosis to temporarily reduce graft blood flow, and then the flow probe was placed 2 cm above the target anastomosis to measure the flow parameters. This method is described as flow reduction TTFM in the rest of the article. Flow parameters associated with each middle distal anastomosis were compared between the two methods. A schematic diagram of both methods is illustrated in Fig. 1.

Evaluation criteria for satisfactory anastomosis. Anastomotic patency was considered satisfactory when the following criteria were met: (i) waveform of blood flow is normal and satisfactory. Blood filling is diastolic dominant. A DF value is $>50\%$, which is consistent with the characteristics of coronary artery blood flow. (ii) PI is acceptable (< 5) [14, 18]. Failure to meet either of the criteria indicated an anastomotic defect and required an immediate revision.

Patients' follow-up visit. All patients came back for follow-up visit 3 months after the surgery. They were examined with electrocardiography and echocardiography during the follow-up visit.

Table 1: Patients' general clinical characteristics before and after surgery

Variables	Before surgery				After surgery	
	Total	Males	Females	P-value	Total	P-value
Patient (number)	84	67	17			
Age (years)	62 ± 9	61 ± 9	64 ± 6	0.14		
Heart rate (bpm)	75 ± 12	74 ± 12	79 ± 10	0.16		
BMI (kg/m^2)	26 ± 3	26 ± 3	25 ± 3	0.34		
LVEF (%)	60 ± 8	60 ± 8	60 ± 9	0.97	64 ± 8	$<0.001^*$
LVEDD (mm)	50 ± 6	50 ± 6	49 ± 5	0.30	45.3 ± 6.1	$<0.001^*$
LVESD (mm)	33 ± 7	34 ± 7	32 ± 7	0.56	29.6 ± 5.3	$<0.05^*$

Data were presented as mean $\pm$ SD.

BMI: body mass index; LVEF: left ventricular ejection fraction; LVEDD: left ventricular end-diastolic diameter; LVESD: left ventricular end-systolic diameter.

*Represented statistically significant different between the total value of before vs after surgery.

Figure 1: Schematic diagram for transit time flow measure (TTFM). (A) Conventional TTFM. Flow probe was placed a few centimetres above a target anastomosis in a sequential graft. (B) Flow reduction TTFM. An atraumatic bulldog clamp was placed at the graft a few centimetres distal to a target anastomosis, and flow probe was placed a few centimetres above the target anastomosis in a sequential graft.

Statistical analysis. Data were presented as mean $\pm$ standard deviation and analysed using the statistical analysing software SPSS (SPSS, Inc., Chicago, IL, USA). Pair-wise comparison was performed by two-tail Student's *t*-test. A *P*-value of <0.05 was considered statistically significant.

RESULTS

The flow reduction method results in significantly lower mean blood flow and higher pulsatility index compared with the conventional method

Among the 84 patients, there were 32 cases of double sequential grafting, 48 of triple sequential grafting and 4 of quadruple sequential grafting. The details of sequential anastomoses are described in Table 2. Flow parameters associated with the middle distal anastomoses were compared between the two methods. In the conventional TTFM, normal blood flow was maintained in a

Table 2: Target vessel of sequential grafting and the number of cases

Sequential graft	Number of cases
SVG-Di-OM	7
SVG-Di-OM-PDA	38
SVG-Di-OM-PLV-PDA	4
SVG-OM-PDA	5
SVG-Di-PLV-PDA	10
SVG-Di-PDA	20

SVG: saphenous vein graft; Di: diagonal artery; OM: obtuse marginal artery; PLV: posterior left ventricular branch; PDA: posterior descending artery.

Figure 2: Comparison of flow parameters measured by the two methods. (A) Comparison of mean blood flow between the conventional transit time flow measurement (TTFM) and the flow reduction TTFM. (B) Comparison of pulsatility index (PI) between the conventional TTFM and the flow reduction TTFM. The graft flow and PI were measure at the middle distal anastomoses to Di, OM and PLV by the two methods. Mean blood flow and PI were calculated from the total patients. Pair-wise Student's *t*-test was performed to compare the values from the two methods. **P* < 0.05 , the flow reduction TTFM vs the conventional TTFM. ****P* < 0.001 , the flow reduction method vs the conventional TTFM.

graft, while in the flow reduction TTFM, the graft blood flow was temporarily reduced during the measurement by placing an atraumatic bulldog clamp a few centimetres distal to the anastomosis to be evaluated (Fig. 1).

As highlighted in Fig. 2A, the mean graft blood flows measured by the flow reduction TTFM near the anastomosis to diagonal artery (Di), obtuse marginal artery (OM) and posterior left ventricular branch (PLV) (25.29 $\pm$ 17.18, 26.55 $\pm$ 21.21 and 18.50 $\pm$ 9.86 ml/min, respectively) were all significantly lower than those measured by the conventional TTFM (58.79 $\pm$ 34.97, 45.17 $\pm$ 26.30 and 37.79 $\pm$ 19.61 ml/min, respectively, *P* < 0.001).

In contrast, the flow reduction TTFM resulted in significantly higher mean PI near the anastomosis to Di, OM and PLV (2.87 ± 1.49 , 2.65 ± 1.29 and 2.37 ± 0.98 , respectively) than the conventional TTFM (2.22 ± 0.94 , 2.05 ± 0.95 and 1.71 ± 0.76 , respectively, $P < 0.05$, Fig. 2B).

We also compared the DF measured by the two methods. As illustrated in Table 3, there was no significant difference in DF between the two methods. All the values were $>50\%$.

The flow reduction transit time flow measurement (TTFM) identifies defective middle distal anastomoses that the conventional TTFM fails to detect

In our study, except one defective posterior descending artery (PDA) anastomosis, all the remaining distal end anastomoses were satisfactory. The defective PDA anastomosis was reconstructed by coronary venous bypass grafting (CVBG), due to the diffuse coronary artery stenosis and the low patency of distal target vessel in this patient. CVBG allows retrograde cardiac perfusion for myocardial [18, 19]. The PI value of the PDA anastomosis was reduced from 5.1 to 3.2, and the graft blood flow was increased from 14 to 67 ml/min after the revision. Interestingly, the flow reduction TTFM identified two defective distal anastomoses that were in the middle of the sequential grafts (Table 4). The PI values associated with the defective Di and OM anastomoses and measured by the flow reduction TTFM were 5.1 and 5.5, respectively, which is considered unacceptable according to the evaluation criteria. However, the PI values collected by the conventional TTFM were

4.7 and 3.7 for the two anastomoses, respectively. These results indicate that the flow reduction method might increase the sensitivity of TTFM to anastomotic defects. The defective Di and OM anastomoses were revised and sutured with a 9-0 Prolene. We believe that a 9-0 Prolene suture could reduce the effect of the suture on the diameter of the anastomosis and improve graft flow effectively. The graft flows near the Di and the OM anastomoses were increased substantially after the revision (Table 4), further suggesting that both anastomoses were defective before the revision.

Follow-up examinations in all patients appear normal

All the 84 patients came back for follow-up visits 3 months after surgery. All the patients exhibited no symptoms associated with heart problems at the follow-up visit. Electrocardiography during the follow-up revealed no newly occurred myocardial infarction. Echocardiography showed that the mean left ventricular ejection fraction was increased to $64 \pm 8\%$ ($P < 0.001$); while the mean left ventricular end-diastolic diameter and mean left ventricular end-systolic diameter were reduced to 45.3 ± 6.1 ($P < 0.001$) and 29.6 ± 5.3 mm ($P < 0.05$), respectively, compared with those prior to the surgery (Table 1).

DISCUSSION

Anastomotic quality is one of the crucial factors affecting the outcome of CABG [8]. Intraoperative TTFM has been widely used to assess anastomotic quality in CABG, because it is non-invasive and easy to use [12]. The PI value is frequently used as an indicator of the quality of an anastomosis. A high PI value usually indicates an anastomotic defect [12, 13, 20], though the cut-off value of PI to represent an imperfect anastomosis has not been standardized. Most surgeons consider that an anastomosis requires a revision if the PI value is >5 [12, 13, 20], others use a PI value of 3 as the cut-off value. Kieser *et al.* [20] investigated the predictive value of intraoperative TTFM for technical errors in grafts and for clinical outcomes on 1000 consecutive arterial grafts. They found that a high PI value (>5) alone could predict technically imperfect arterial grafts during operation and the mortality of the patients undergoing the operation [20]. On the other hand, Di Giammarco *et al.* [16] have found that a PI value of ≥ 3 is independently correlated with a higher incidence of graft failure. In this study, we used a PI value of 5 as the cut-off criterion for an unsatisfactory anastomosis, and totally three defective anastomoses with associated PI values >5 were identified by our TTFM methods. One was a PDA anastomosis at the distal end of the sequential graft, and the remaining two anastomoses, one to Di and one to OM, were middle anastomoses of the sequential grafts. After revision, the graft flows associated with the three anastomoses were all improved significantly. We believe that the cut-off value of PI should be determined by the type of transit time flow metre, a surgeon's accumulated experience in performing the intraoperative flow measurement and the accumulated patients' data on intraoperative flow measurement. Nordgaard *et al.* [21] have reported that the PI value varies between two different transit time flow metres. We have been routinely using the same type of transit time flow metre (MediStim) on a daily basis for many years

Table 3: Diastolic filling measured by the two methods

	Number of cases	Conventional TTFM (%)	Flow reduction TTFM (%)	P-value
Di	66	71.20 ± 7.93	70.82 ± 11.43	0.71
OM	40	69.53 ± 11.05	71.28 ± 8.06	0.33
PLV	12	68.42 ± 8.53	66.50 ± 6.19	0.43

Data were presented as mean $\pm$ SD.

Di: diagonal artery; OM: obtuse marginal artery; PLV: posterior left ventricular branch; TTFM: transit time flow measurement.

Table 4: Comparison of pulsatility index (PI) and graft flow between before and after the revision

Case	Target vessel	Before/after revision (B/A)			
		Conventional TTFM		Flow reduction TTFM	
		PI (B/A)	Graft flow (B/A)	PI (B/A)	Graft flow (B/A)
1	Di	4.7/2.1	93/97	5.1/2.6	0/66
2	OM	3.7/3.3	32/43	5.5/4.1	15/18

Di: diagonal artery; OM: obtuse marginal artery; TTFM: transit time flow measurement.

in our hospital. The average number of off-pump CABG we perform every month is 100 in our hospital. In our experience, a PI of >5 combined with low graft flow usually indicates an anastomotic imperfection and prompts us to re-examine the anastomosis and repair the defect. The significant improvement of PI and graft flow after anastomotic reconstruction for the 3 cases in this study suggests that a PI of 5 seems to be a reasonable cut-off value for intraoperative assessment of anastomotic quality in our patients.

The improvement of graft flows after the revision of the three imperfect anastomoses suggests that those anastomoses were defective before revision. It would be great to perform angiography to further assess anastomotic quality in addition to TTFM in our study. However, angiography is invasive, expensive and difficult and could also expose patients to serious risks, such as internal bleeding and infection. Thus, angiography is usually not performed during patients' follow-up visit in clinical practice. Coronary computed tomography angiography (CCTA) might be a promising alternative to invasive angiography due to its non-invasiveness. CCTA is now commonly used in clinics to exclude obstructive coronary artery disease because of its high sensitivity and very good negative predictive value. It is also reported that CCTA can be used to accurately assess graft patency following CABG [22–24]. In our hospital, we use CCTA mainly for the diagnosis of suspected coronary artery disease. Due to patients' concern about the economic burden and radiation exposure associated with CCTA, we have not yet used it as a routine procedure to assess graft patency after CABG. As both the temporal and spatial resolution of CCTA have been increasingly improved, we are expecting to use CCTA more in our hospital and are certainly considering using this approach to assess graft patency in our future studies.

In this study, we performed echocardiography on all patients in the follow-up, and the results suggested that the patients' heart function was improved after the operation. The 3 patients who had the anastomotic reconstruction during the operation all exhibited significantly improved blood flow through the heart in the echocardiography examination during the follow-up visit compared with the condition prior to the operation. The good test results from follow-up and the improvements of graft flow pattern after the revision for the two middle defective anastomoses indicate that the flow reduction TTFM might be more sensitive to anastomotic errors than the conventional TTFM, particularly to those less-than-critical errors that could be missed by the conventional TTFM.

In the conventional method for TTFM, graft flow characteristics are usually measured when normal blood flow in a graft is maintained. For a sequential graft, the flow parameters collected by the conventional TTFM represent total graft flow, and these flow parameters are good indicators for a problematic anastomosis only when the anastomotic defect causes substantial changes in the graft flow. In our study, the defective PDA anastomosis, which was the distal-end anastomosis in the sequential graft, was identified based on the PI value of the total graft flow. The graft flow was increased from 14 to 67 ml/min after the revision of the defective PDA anastomosis. However, a less-than-critical anastomotic error might not affect the graft flow significantly. Based on a complex mathematical analysis of the flow curve, it is suggested that a stenosis causing a 50% or greater narrowing of anastomoses can affect graft flow substantially and enable detection by TTFM [25]. In addition, it has been found that the transit time blood flow in a sequential graft is substantially higher than that in a single graft [1,

17], which could further mask the effect of a less-than-critical defective anastomosis on the total graft flow. We believe that the two anastomotic defects identified by the flow reduction method might not be so critical as to significantly reduce the total graft flow. In fact, the graft flows near the two defective middle anastomoses measured by the conventional TTFM (Di: 93 and OM: 32 ml/min) appeared normal before the revision, although they were both increased after the anastomoses were repaired (Di: 97 ml/min and OM: 43 ml/min). In contrast, the graft flows near the two anastomoses measured by the flow reduction method (0 and 15 ml/min) were significantly lower than those collected by the conventional TTFM, resulting in the PI values of >5, which prompted us to reconstruct the problematic anastomoses. After the revision, the graft flows measured by the flow reduction method were increased significantly from 0 and 15 to 66 and 18 ml/min, respectively.

We believe that a less-than-critical anastomotic error in a sequential graft might pose a significantly higher risk of failure of revascularization than that in an individual graft if it is not repaired promptly during the operation, because a stenosis or an occlusion in a sequential graft could potentially have adverse effects on multiple target coronary vessels. Thus, it is crucial to detect anastomotic defects during the operation for the long-term success of sequential vein grafting. In this study, we improved the sensitivity of intraoperative TTFM to defective anastomoses in sequential grafts by using an atraumatic bulldog clamp to temporarily reduce the graft flow during the measurement. We propose that the temporary reduction of graft flow seems to simplify the complex haemodynamics in a sequential vein graft into a blood flow pattern that resembles the haemodynamics in a single vein graft. Our flow reduction TTFM might temporarily reduce the blood flow in a sequential graft to the level of a single vein graft, which results in the increase of the PI value according to the equation $PI = [(\text{maximum volumetric peak flow } (Q_{\max}) - \text{minimum volumetric peak flow } (Q_{\min})) / \text{mean volumetric flow } (Q_{\text{mean}})]$ [14]. The difference between $Q_{\max}$ and $Q_{\min}$ is usually constant, and thus, reduced Q_{mean} in the flow reduction method leads to an elevated PI value.

In summary, the flow reduction method appears to be able to accurately assess the quality of every distal anastomosis in a sequential graft. Temporary reduction of graft flow during intraoperative TTFM seems to improve the sensitivity of TTFM to defective anastomoses in sequential grafts and allow for prompt revision of the defective anastomoses. Thus, the flow reduction TTFM might increase the success rate of sequential vein grafting and improve the long-term outcomes of patients.

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REFERENCES

- [1] Coronary artery surgery study (CASS). A randomized trial of coronary artery bypass surgery. Survival data. *Circulation* 1983;68:939–50.
- [2] Magee MJ, Coombs LP, Peterson ED, Mack MJ. Patient selection and current practice strategy for off-pump coronary artery bypass surgery. *Circulation* 2003;108:119–14.

- [3] Emmert MY, Salzberg SP, Seifert B, Schurr UP, Hoerstrup SP, Reuthebuch O *et al.* Routine off-pump coronary artery bypass grafting is safe and feasible in high-risk patients with left main disease. *Ann Thorac Surg* 2010; 89:1125–30.
- [4] Kappetein AP, Feldman TE, Mack MJ, Morice MC, Holmes DR, Stähle E *et al.* Comparison of coronary bypass surgery with drug-eluting stenting for the treatment of left main and/or three-vessel disease: 3-year follow-up of the syntax trial. *Eur Heart J* 2011;32:2125–34.
- [5] Farsak B, Tokmakoglu H, Kandemir O, Günaydin S, Aydin H, Yorgancioglu C *et al.* Angiographic assessment of sequential and individual coronary artery bypass grafting. *J Card Surg* 2003;18:524–9; discussion 530–1.
- [6] Kandemir O, Tokmakoglu H, Tezcaner T, Yorgancioglu C, Suzer K, Zorlutuna Y. Right coronary system grafts: alone or together with left system grafts—angiographic results. *Ann Thorac Cardiovasc Surg* 2007;13:27–31.
- [7] Beldi G, Bosshard A, Hess OM, Althaus U, Walpoth BH. Transit time flow measurement: experimental validation and comparison of three different systems. *Ann Thorac Surg* 2000;70:212–7.
- [8] Hirotani T, Kameda T, Shiota S, Nakao Y. An evaluation of the intraoperative transit time measurements of coronary bypass flow. *Eur J Cardiothorac Surg* 2001;19:848–52.
- [9] Kjaergard HK, Irmukhamedov A, Christensen JB, Schmidt TA. Flow in coronary bypass conduits on-pump and off-pump. *Ann Thorac Surg* 2004; 78:2054–6.
- [10] Onorati F, Pezzo F, Esposito A, Impiombato B, Comi MC, Polistina M *et al.* Single versus sequential saphenous vein grafting of the circumflex system: a flow metric study. *Scand Cardiovasc J* 2007;41:265–71.
- [11] Nordgaard H, Vitale N, Haaverstad R. Transit-time blood flow measurements in sequential saphenous coronary artery bypass grafts. *Ann Thorac Surg* 2009;87:1409–15.
- [12] D'Ancona G, Karamanoukian HL, Ricci M, Bergsland J, Salerno TA. Graft patency verification in coronary artery bypass grafting: principles and clinical applications of transit time flow measurement. *Angiology* 2000; 51:725–31.
- [13] D'Ancona G, Karamanoukian HL, Ricci M, Schmid S, Bergsland J, Salerno TA. Graft revision after transit time flow measurement in off-pump coronary artery bypass grafting. *Eur J Cardiothorac Surg* 2000;17:287–93.
- [14] Leong DK, Ashok V, Nishkantha A, Shan YH, Sim EK. Transit-time flow measurement is essential in coronary artery bypass grafting. *Ann Thorac Surg* 2005;79:854–7; discussion 857–8.
- [15] Walpoth BH, Bosshard A, Genyk I, Kipfer B, Berdat PA, Hess OM *et al.* Transit-time flow measurement for detection of early graft failure during myocardial revascularization. *Ann Thorac Surg* 1998;66:1097–100.
- [16] Di Giammarco G, Pano M, Cirmeni S, Pelini P, Vitolla G, Di Mauro M. Predictive value of intraoperative transit-time flow measurement for short-term graft patency in coronary surgery. *J Thorac Cardiovasc Surg* 2006;132:468–74.
- [17] Kim HJ, Lee TY, Kim JB, Cho WC, Jung SH, Chung CH *et al.* The impact of sequential versus single anastomoses on flow characteristics and mid-term patency of saphenous vein grafts in coronary bypass grafting. *J Thorac Cardiovasc Surg* 2011;141:750–4.
- [18] Yu Y, Yan XL, Wei H, Yang JF, Gu CX. Off-pump sequential bilateral internal mammary artery grafting combined with selective arterialization of the coronary venous system. *Chin Med J (Engl)* 2011;124:3017–21.
- [19] Yu Y, Qi DN, Gu CX. Sequential saphenous vein grafting combined with selective arterialization of middle cardiac vein during off-pump coronary artery bypass surgery. *Chin Med J (Engl)* 2010;123:2739–40.
- [20] Kieser TM, Rose S, Kowalewski R, Belenkie I. Transit-time flow predicts outcomes in coronary artery bypass graft patients: a series of 1000 consecutive arterial grafts. *Eur J Cardiothorac Surg* 2010;38:155–62.
- [21] Nordgaard HB, Vitale N, Astudillo R, Renzulli A, Romundstad P, Haaverstad R. Pulsatility index variations using two different transit-time flow meters in coronary artery bypass surgery. *Eur J Cardiothorac Surg* 2010;37:1063–7.
- [22] Jones CM, Athanasiou T, Dunne N, Kirby J, Aziz O, Haq A *et al.* Multi-detector computed tomography in coronary artery bypass graft assessment: a meta-analysis. *Ann Thorac Surg* 2007;83:341–8.
- [23] Houslay ES, Lawton T, Sengupta A, Uren NG, McKillop G, Newby DE. Non-invasive assessment of coronary artery bypass graft patency using 16-slice computed tomography angiography. *J Cardiothorac Surg* 2007; 2:27–35.
- [24] Bassri H, Salari F, Noohi F, Motevali M, Abdi S, Givtaj N *et al.* Evaluation of early coronary graft patency after coronary artery bypass graft surgery using multislice computed tomography angiography. *BMC Cardiovasc Disord* 2009;9:53–8.
- [25] Cerrito PB, Koenig SC, Koenig SC, Jaber SF, Ewert DL, Spence PA. Neural network pattern recognition analysis of graft flow characteristics improves intraoperative anastomotic error detection in minimally invasive CABG. *Eur J Cardiothorac Surg* 1999;16:88–93.