# THE USE OF THERMAL IMAGER TO ASSESS THE ADEQUACY OF MYOCARDIAL REVASCULARIZATION IN CORONARY BYPASS SURGERY

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**ABSTRACT**

Over the past two years, thermal imaging complex (TIC) NEC TH-9100 has been used in all patients undergoing coronary bypass surgery in the department of emergency coronary surgery to assess the state of the coronary arteries, adequacy of distal anastomosis, and effectiveness of myocardial revascularization.

Good visualization of coronary blood flow with an aid of intraoperative thermal coronary angiography made it possible to determine the minimum required (rational) amount of myocardial revascularization in each case.

**CONCLUSION**

The use of TIC during coronary bypass surgery allows to assess the state of the coronary arteries in real time, as well as localize subepicardial coronary arteries and assess the anastomotic adequacy and myocardial perfusion after revascularization.

**Keywords:** thermal coronary angiography, coronary artery bypass.

ADA — anterior descending artery
CA — circumflex artery
CAs — coronary arteries
CAG — coronary angiography
CHD — coronary heart disease
CS — cardioplegic solution
CVAG — coronary ventricular angiography
EchoCG — echocardiography
LCA — left coronary artery
LITA — left internal thoracic artery
LV — left ventricle
OMB — obtuse marginal branch
TIC — thermal imaging complex
TCA — thermal coronary angiography

## INTRODUCTION

Despite the progress made over the past decade in treatment, coronary heart disease (CHD) still occupies a leading position for morbidity and mortality in developed countries. Myocardial revascularization is one of the most effective treatments for patients with coronary heart disease.

Visualization of coronary arteries (CAs) during surgery to assess their condition, choice of the optimal location for distal anastomoses between autografts and CAs and assessing its performance as well as adequacy of myocardial revascularization have been topical issues since the beginning of coronary surgery development.

To solve this problem, various methods have been proposed over the years, but they either do not have sufficient resolution or require expensive equipment and consumables, or not allow to perform comprehensive evaluation of CAs condition in real time.

## THE HISTORY OF THERMAL IMAGING DEVELOPMENT IN CORONARY SURGERY

The first works, devoted to the use of thermal imaging technology in coronary surgery, appeared in 1978, when changes in the size of ischemic areas after formation of anastomoses between autovenous grafts and CAs were examined with the help of cold solutions or warm blood [1].

In 1979, there were studies showing that using thermal cameras can help visualize the area of myocardial perfusion when introducing cold saline solution into the bypass [2].

Further development of thremal imaging technique was studied by various authors [3-9], who noted the possibility to visualize not only CAs in different systems, but also sites of stenosis, as well as operator errors during the formation of anastomoses. Thus, they confirmed that thermal coronary angiography (TCAG) was a promising technique to assess the adequacy of myocardial revascularization.

In Russia, first attempts to apply the thermal imaging complex (TIC) were taken in coronary surgery in 1996 [10]. TIC *OPGAL-IVA-2000, GE* gave images of acceptable quality for further analysis, which confirmed the effectiveness of its use in coronary surgery. However, there were disadvantages such as complexity of manipulations, bad layout, making it difficult to be used in the operating room, as well as a very high cost.

The next stage in the development of TCAG in Russia was the use of TIC *VasoTherm -1,* developed by *IRTIS (Russia)* and tested in the clinic [11-13].

It was a scanning thermal imaging camera, not allowing to get high quality images in real time.

A significant step forward in coronary surgery, in particular in the domestic medicine was the use of a thermal imager *NEC TH-9100* during myocardial revascularization together with techniques developed in the Department of Emergency Coronary Surgery, N.V. Sklifosovsky Research Institute for Emergency Medicine together with ZAO (JSC) "Matrix Technologies" [14].

Widespread coronary bypass surgery inevitably leads to a constant increase in the number of patients with recurrent angina [15]. There are many publications in the medical literature which analyze causes of the disease recurrence after surgery, and the main ones are stenosis or occlusion of grafts, progression of atherosclerosis in coronary arteries and incomplete revascularization [16-22].

Proper surgical tactics during myocardial revascularization in patients with coronary heart disease largely determines the prognosis for the life of each individual patient. Most authors [23-26] agree that complete revascularization definitely has better performance than partial revascularization. In patients with complete myocardial revascularization there is lower incidence of recurrent angina and the need for repeated surgery than in patients with partial myocardial revascularization, although the frequency of deaths in the immediate and long-term period are not significantly different. Prior to the use of TCAG during myocardial revascularization operations, we had also sought to restore blood flow in all CAs with hemodynamically significant stenosis, if their diameter was 1 mm or more.

It should be noted that the concept of adequate myocardial revascularization is not always determined by the number of distal anastomoses. The results of surgical treatment is significantly influenced by the initial functional condition of the heart, type of CAs lesion and the diameter of vessels to be bypassed, degree of stenosis and adequate blood flow, individual characteristics of coronary blood supply, as well as vascular grafts quality. A compromise between the justifiable desire to perform complete myocardial revascularization, as well as reasonability of making bypasses for all of the affected CAs should exclude extreme positions: the dangerous overextension to unreasonabe reduction in myocardial revascularization.

Our research aimes to figure out whether TCAG helps to determine the minimum number of distal anastomoses between autografts and CAs in each case with safe and effective revascularization of myocardium, when performing coronary bypass surgeries . That is, in other words, to perform "rational" myocardial revascularization.

**Objective.** To study the possibility of using *NEC TH-9100* to determine the optimal number of distal anastomoses during coronary bypass surgery and assess an adequacy of myocardial revascularization.

## MATERIALS AND METHODS

The study included 792 patients with severe coronary heart disease (unstable angina, non-*Q* wave myocardial infarction, early post-infarction angina) who underwent myocardial revascularization surgery with cardiopulmonary bypass. All patients were divided into 2 groups. The Group 1 included 398 patients operated from January 2012 to January 2014, with complete myocardial revascularization without the use of a thermal imager. The Group 2 included 394 patients operated from January 2014 to January 2016, with"rational" myocardial revascularization using TIC *NEC TH-9100 (Japan)* intraoperatively.

Groups of patients were comparable in age, nosology, and comorbidities (Table 1).

*Table 1*

**Characteristics of patients**

| | Patients with complete revascularization, *n*=398 (%) | Patients with rational revascularization, *n*=394 (%) | Statistical significance, *p* |
|---|---|---|---|
| Age: 34-85 years | 58.4±9.4 | 57.4±7.4 | > 0.05 |
| Male | 354 (89) | 362 (92) | <0.05 |
| Female | 44 (11) | 32 (8) | > 0.05 |
| Previous myocardial infarction | 326 (82) | 315 (80) | > 0.05 |
| Postinfarction left ventricular aneurysm | 76 (19) | 67 (17) | > 0.05 |
| Circulatory insufficiency II A degree | 223 (56) | 209 (53) | > 0.05 |
| Hypertension stage 3 | 374 (94) | 362 (92) | > 0.05 |
| Acute cerebrovascular accident in history | 12 (3) | 6 (1.5) | > 0.05 |
| Diabetes | 56 (14) | 49 (12.5) | > 0.05 |
| Gastric ulcer/duodenal ulcer | 119 (29.9) | 113 (28.6) | > 0.05 |
| Scale *GRACE* | 146±8 | 144±6 | > 0.05 |
| Scale *EuroSCORE II* | 7.4±0.4 | 7.3±0.2 | > 0.0 |

The statistically significant difference in the groups was determined by Pearson's test ($\chi^2$).

The vast majority of patients in both groups were male. The average age in Group 1 was 58.4±9.4 years and 57.4±7.4 years in Group 2.

All patients underwent coronary ventricular angiography (CVAG) in order to visualize CAs and assess the degree of its lesion.

Patients were also comparable in two groups by the type of CAs lesion (Table 2). According to coronary angiography (CAG), critical multivessel CAs lesion was revealed in all patients. Most patients in both groups had stenosis of the left main coronary artery (LCA) and its equivalent — 69.8% in Group 1 and 64.6% in Group 2.

*Table 2*

**Findings of coronary ventricular angiography**

| | Patients with complete revascularization, *n*=398 (%) | Patients with rational revascularization, *n*=394 (%) | Statistical significance, *p* |
|---|---|---|---|
| Single vessel lesion | (0) | (0) | |
| Two vessels lesion | 18 (4.6) | 24 (6.1) | <0.05 |
| Three vessels lesion | 378 (94.9) | 370 (93.9) | >0.05 |
| Stenosis of the left main coronary artery or its equivalents | 278 (69.8) | 255 (64.6) | >0.05 |
| Signs of left ventricular aneurysm | 41 (10.3) | 61 (15.5) | <0.05 |
| Ejection fraction | | | |
| Less than 40% | 56 (14.0) | 64 (16.3) | >0.05 |
| More than 40% | 342 (86.0) | 330 (83.7) | >0.05 |

All patients underwent transthoracic echocardiography (if indicated, transesophageal echocardiography, stress echocardiography with low-dose dobutamine, radioisotope study of the myocardium at rest and with drug test) to assess the functional state of the heart.

During the surgery, all patients underwent transesophageal echocardiography to assess cardiac output in postperfusion period and the adequacy of myocardial revascularization.

Great saphenous veins, radial arteries and the left internal thoracic artery (LITA) were used as autografts. The state and properties of vascular grafts prior to surgery were confirmed by Doppler ultrasonography (great saphenous veins, radial artery) and angiography (LITA).

Myocardial revascularization operations were carried out using a multi-component balanced anesthesia under the standard methods of cardiopulmonary bypass. Consol solution or a solution based on blood were used as cardioplegic solutions.

Grafts as linear and sequential bypasses were primarily used for myocardial revascularization. Natural autovenous branching and *T*-shaped designs of the grafts were also applied. LITA was normally used to bypass the left anterior descending artery in all patients. If necessary, endarterectomy of CAs was performed.

Surgical interventions are presented in Table 3.

*Table 3*

**Surgical interventions**

| | Patients with complete revascularization, *n*=398 | Patients with rational revascularization, *n*=394 |
|---|---|---|
| Isolated coronary artery bypass | 369 | 376 |
| Coronary bypass surgery + aortic valve or mitral valve replacement | 7 | 2 |
| Coronary bypass surgery combined with different methods of left ventricular cavity plastics | 16 | 11 |
| Coronary bypass surgery combined with endarterectomy of the internal thoracic artery | 6 | 5 |

## THE TECHNIQUE OF USING THERMAL IMAGING COMPLEX DURING CORONARY ARTERY BYPASS SURGERY TO ASSESS THE ADEQUACY OF MYOCARDIAL REVASCULARIZATION

When surgery begins, TIC is installed in the operating room at the patient's head and palette is adapted for operating conditions in the temperature from +4° C to 30° C (depending on the stage of operation). The monitor, where an image is projected, is opposite to an operating surgeon. Cardiopulmonary bypass is initiated, the aorta is cross-clamped and myocardium is arrested by using refrigerated (to +4° C) cardioplegic solution (CPS), and then, visual and palpation exploration of CAs is performed. In cases where it is impossible to locate CAs because of their intramyocardial position or involvement in the scar tissue due to significant Dressler syndrome, TCAG is performed with the use of TIC.

The camera focuses on the surface of the heart and cooled cardioplegic solution is introduced into the aorta. Coronary flow is visualized due to the appearance of a temperature gradient between the epicardium and the vascular wall. More clear visualization of CAs can be obtained by increasing the temperature gradient "epicardium-coronary vessel", which is achieved by single irrigation of a heart surface by isotonic solution of indoor temperature.

The time required for CAs clear visualization on the TIC monitor is 5-40 seconds. This is due to the varying thickness of epicardium and fat above CAs in different parts, different depth of CAs location in the myocardium, or scars and the presence of stenosis along arteries right to occlusion.

TCAG may detect CAs (thus reducing the time to search for them), carry out a qualitative assessment of its condition (detection of areas with stenosis) and choose the optimal location for the formation of anastomosis with an autograft.

After forming the distal anastomosis, cold (6-10° C) saline in a volume of 20-30 ml is introduced into the autograft via a syringe. When a cold solution passes along the graft and then along CAs, TIC monitor clearly visualize the area of the distal anastomosis and coronary flow with revascularization area in real-time.

According to the obtained image, the quality of anastomosis is assessed, and technical errors, if any, are revealed (anastomotic defects, assessment of its integrity). The next step is evaluation of myocardial revascularization adequacy in the ischemic area and the need to perform additional bypass of near CAs. If the graft sufficiently fills a coronary flow the with a saline below the distal anastomosis and adjacent coronary arteries through intra- and inter-system collaterals or retrogradely, with a good myocardial perfusion in the ischemic area, then the additional bypass operation is not performed in this area.

As an example, we present a coronary angiography image of a female patient with occlusion of a large obtuse marfinal branche, which provided the blood supply of an extensive area of the lateral LV wall (Fig. 1) and intraoperative photo (Fig. 2) of the same patient made by a thermal imager after revascularization in the area.

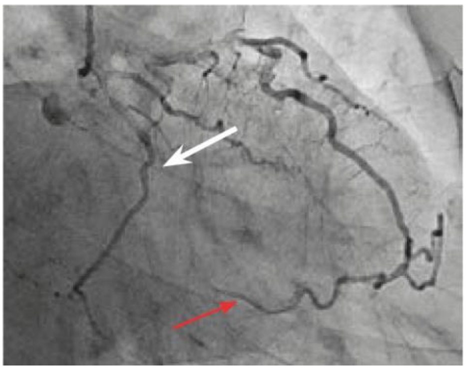

Fig. 1. Coronary angiography image of a patient before surgery. The white arrow indicates obtuse marginal branch occlusion. The red arrow indicates distal parts of obtuse marginal branch

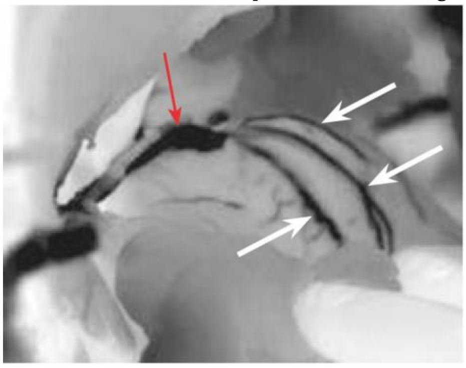

Fig. 2. The process of filling the cold saline into autovenous graft (red arrow) and obtuse marginal branch (white arrow) on the lateral LV wall. The image was made by a thermal imager.

As can be seen in Fig. 2, a linear bypass (great saphenous vein) made it possible to restore blood flow in OMB with good filling of adjacent arteries. It resulted in restored myocardial perfusion throughout the ischemic area, which indicates that the distal anastomosis was properly located and myocardial revascularization was adequately performed.

Despite the satisfactory filling of coronary flow with a saline through the graft below the distal anastomosis, addidional coronary bypasses were made in order to provide the sufficient perfusion of ischemic area if near located arteries with hemodynamically significant stenoses were not filled (no intra- and intersystem collaterals, significant stenosis in the arteries, preventing retrograde blood flow).

A good example is the intraoperative photo of a male patient (Fig. 3), made by the imager after formation of distal anastomosis between the autovenous graft and circumflex artery (CA) on the lateral LV wall.

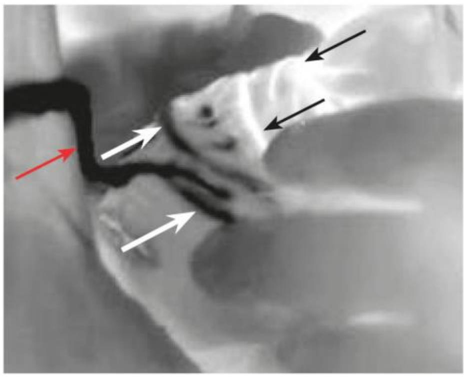

Fig. 3. The process of filling the autovenous graft (red arrow) and the circumflex artery and its branches (white arrows) with a cold saline. Black arrows indicate branches of the right coronary artery. The lack of intersystem collaterals is clearly seen. The image was obtained with the thermal imager from the patient's head. The apex of the heart is rotated to the head slightly to the left. The posterior surface of the heart is visible.

The presented thermal coronary angiography image clerary shows that after bypass surgery and application of cold saline solution through the vein graft, the good filling of coronary arteries (CA, OMB) below the anastomosis was observed, but there was no filling of adjacent branches of the right CA (indicating the absence of intersystem collaterals). According to the coronary angiography image of the same patient (Fig. 4), there is a diffuse lesion of the right CA with hemodynamically significant stenosis in its proximal part. The patient underwent bypass surgery of the posterior descending artery (Fig. 5). Thus, an adequate blood supply of the posterolateral LV wall was restored.

Fig. 4. Coronary angiography image of a patient before surgery.
The red arrow shows the right coronary artery. The green arrows show posterior descending artery and posterior lateral branch.

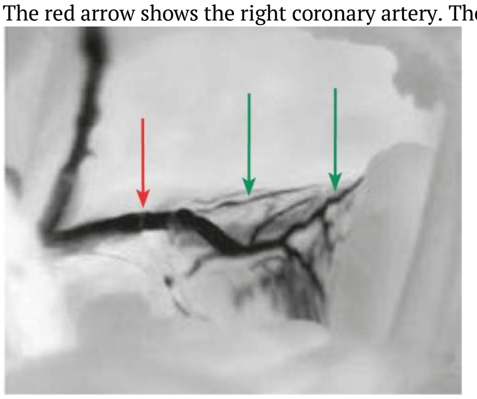

Fig. 5. The process of filling the autovenous graft (red arrow) and the right coronary artery branches (green arrows) with a cold saline. The image was made with a thermal imager.

TIC imaging is made stage-by-stage for each branch or part of a graft, when performing sequential anastomoses, or when an autovenous graft with natural branching or T-shape construction made of autografts are used.

The quality of the formed anastomosis between LITA and the anterior descending artery (LAD) and the adequacy of myocardial revascularization are estimated after restoration of blood flow in the arterial bypass (according to the image on the TIC monitor, the rate of vascular pattern appearance and intensity of myocardial warming).

We present the coronary angiography image of a male patient with subtotal stenosis of the LAD before discharge of the diagonal branch (Fig. 6) and intraoperative photos (Fig. 7) of the same patient made by the thermal imager, after revascularization of the anterolateral wall of the left ventricular myocardium. It is clearly seen that using a single LITA succeeded in restoring good blood flow in the LAD and diagonal branch (the diagonal branch is filled retrogradely through LAD), which indicates that the distal anastomosis was formed properly and myocardial revascularization was adequately performed. The bypass of a diagonal branch would create a competitive bloodstream in this case.

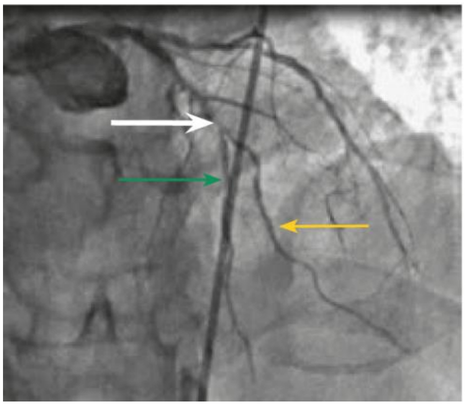

Fig. 6. Coronary angiography image of a patient before surgery.

The green arrows indicate anterior descending artery. The yellow arrow indicates a diagonal branch. The white arrow indicates the stenosis.

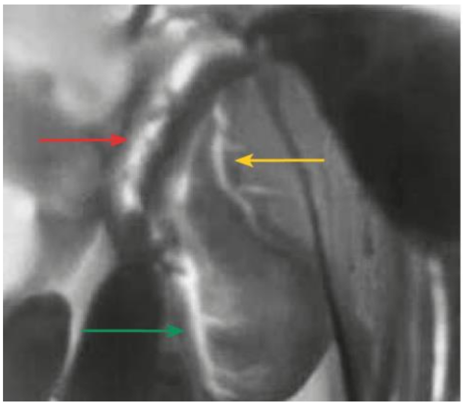

Fig. 7. The process of filling the left anterior descending artery (green arrow) and the diagonal branch (yellow arrow) with blood through the left internal thoracic artery (red arrow). The image was made with a thermal imager.

When all anastomoses are performed and coronary flow restores, the completeness of revascularization is assessed. After reperfusion and restoration of blood flow with the help of TIC, the intensity of myocardial warming is clearly seen, which may indirectly show the quality of perfusion in different sites (Fig. 7).

## RESULTS

A clear thermal coronary angiography images of CAs were made in all cases of non-occluding lesion. If coronary arteries were occluded, the time of coronary filling and clear visualization directly depended on the presence of collaterals.

In 6 patients, TIC helped detect coronary arteries location (which was not possible with the conventional visual examination and palpation of the epicardium) and determine optimal location for anastomotic formation. Of these, 2 patients had significant Dressler's syndrome, and in 4 patients, coronary arteries were located deep subepicardially.

We studied 1,482 distal anastomoses in 394 patients: 1,024 anastomoses between autovenous grafts and CAs, and 458 anastomoses between arterial grafts (LITA, radial arteries) and CAs.

In 8 patients, the anastomotic leakage was detected during introduction of cold saline through the bypass as extravasation ("heat spot"), which was not visible during normal examination. Thermal imaging helped clearly identify the defect location and perform sealing of anastomosis prior to blood flow initiation, thus avoiding subsequent additional stitching in the anastomotic area on a beating heart.

In 3 patients, TCAG revealed noted the lack of adequate blood flow after formation of the distal anastomosis between the autograft and CA, which required additional exploration of anastomosis and re-stiching.

Detection of intramyocardially located CAs with TIC, and identification of deficiencies immediately after the formation of distal anastomoses allowed to avoid serious complications in the future.

In all 394 patients (after restoration of blood flow in the autograft and the restoration of normal cardiac activity) we noted the absence of significant thermal gradients on the surface of various myocardial areas that, in our opinion, shows "sufficient" and "adequate" myocardial revascularization. The adequacy of myocardial revascularization was also confirmed by myocardial contractility by means of transesophageal echocardiography in postperfusion period.

In our view, the gradual evaluation of blood flow in CAs through sequential anastomoses, natural branching and formed T-shaped constructions allows to assess the completeness and quality of myocardial revascularization, as well as to avoid the formation of unnecessary anastomoses.

It is well known that reduction of the number of distal anastomoses may decrease the time of myocardial ischemia and cardiopulmonary bypass, which in turn has a positive effect on surgery results.

So, the use of TIC and new tactics of surgical myocardial revascularization, the average number of distal anastomoses in the last 2 years decreased from 4.7 to 3.7 compared to previous years. In this case, comparing the results of surgical treatment in the immediate and long-term period in patients with the most complete restoration of blood flow in all the affected arteries and in patients with a rational approach in determining the number of distal anastomoses, we found no statistically significant difference in the recurrence rate of angina and mortality (Table 4).

*Table 4*

**Results of surgical treatment in patients with complete and "rational" revascularization in the immediate and late postoperative period**

| | Early results | | |
|---|---|---|---|
| | Patients with complete revascularization *n* =398 | Patients with rational revascularization *n*=394 | Statistical significance, *p* |
| Myocardial infarction time, min | 55.3±10.1 | 45.1±5.3 | <0.05 |
| Cardiopulmonary bypass time, min | 80.5±15.4 | 60.3±10.4 | <0.05 |
| Number of distal anastomoses | 4.7 | 3.7 | |
| Deaths from cardiac causes | 9 (2.2%) | 9 (2.3)% | >0.05 |
| | Long-term results. Periods of observation from 3 to 21 months (11.3 months averagely) | | |
| | *n*=84 | *n*=86 | |
| No angina | 80 (95.2%) | 80 (93.0%) | >0.05 |
| Angina of 2-3 functiontional class | 4 (4.7%) | 5 (5.8%) | >0.05 |
| Myocardial infarction after discharge | 1 | 2 | |
| Tolerance to stress : | | | |
| Negative load test | 79 (94.1%) | 80 (93.1%) | >0.05 |
| Positive load test, average tolerance | 5 (5.9%) | 6 (6.9%) | >0.05 |
| Deaths of cardiac causes | - | - | |

## CONCLUSION

Intraoperative thermal coronary angiography with an aid of TIC is an effective safe method for real-time visualization of the coronary bed, assessing the state of grafts and the quality of anastomoses. TIC helps determine the optimal (rational) number of distal anastomoses with effective, safe and adequate myocardial revascularization, as it visualizes the myocardial blood supply after each newly formed distal anastomosis with high accuracy, which in turn prevents formation of excess anastomoses and creating competitive conditions of blood flow in the bypass. It should be noted that evaluation of revascularization completeness using TIC at this stage is qualitative and requires further development to expand its functionality.

Currently, we work on the improvement of TIC capabilities and software that later would allow to make a quantitative analysis of myocardial perfusion areas. This, in turn, will help assess the completeness and adequacy of myocardial revascularization better.

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**Article received on March 10, 2016**



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