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Diagnostic radiology methods for assessing coronary artery bypass graft viability

Vesnina Zh.V., Grakova E.V.

*Cardiology Research Institute, Tomsk National Research Medical Center (NRMC), Russian Academy of Sciences
111a, Kievskaya Str., Tomsk, 634012, Russian Federation*

ABSTRACT

The review describes available modern radiological methods which are currently applied for a detailed and comprehensive anatomical and functional assessment of the viability of various coronary artery bypass grafts. In addition, it presents some aspects of the implementation of these methods and clinical interpretation of the results.

Keywords: coronary artery bypass grafting, arterial and venous conduits, diagnostic radiology methods

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Лучевые методы диагностики в оценке состоятельности коронарных шунтов

Веснина Ж.В., Гракова Е.В.

*Научно-исследовательский институт (НИИ) кардиологии,
Томский национальный исследовательский медицинский центр (НИМЦ) Российской академии наук
634012, Россия, г. Томск, ул. Киевская, 111а*

РЕЗЮМЕ

В обзоре представлено описание лучевых инструментов и методов, доступных в настоящее время, для получения тщательной и полной анатомической и функциональной оценки состоятельности различных коронарных шунтов, а также некоторые детали выполнения и клинической интерпретации результатов этих исследований.

Ключевые слова: аортокоронарное шунтирование, артериальные и венозные кондуиты, лучевые методы диагностики

✉ *Vesnina Zhaneta V.,* zhvesnina@mail.ru

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INTRODUCTION

Coronary artery disease (CAD) is one of the leading causes of morbidity and mortality worldwide, affecting nearly 20% of people over 65 years [1] and accounting for 370,000 deaths each year [2]. The clinical and prognostic benefits of coronary artery bypass grafting (CABG) are well accepted, because the surgical method allows to achieve complete revascularization in patients with multivessel CAD and is performed in over 1 million patients annually [3]. Although the 5-year survival after CABG is 75–80% [4, 5], nearly 20% of patients develop congestive heart failure (CHF) within 2 years after the surgery [6]. CABG provides excellent short- and intermediate-term results, but a long-term outcome is highly dependent on the patency of the vascular conduits used.

Venous grafts are more susceptible to the development of pathological changes due to the fact that the structure of the vessel itself is not designed for high blood pressure. Impaired vascular tone, vessel dilation, and slowed blood flow can eventually cause thrombosis of the graft. Over time, the venous conduit can adapt to the arterial blood flow, but becomes susceptible to atherosclerotic damage [7, 8]. The use of arteries similar in their anatomical structure to coronary vessels gives a much better result, but arteries also differ from each other in their biological characteristics.

Currently, internal thoracic (mammary) arteries (ITA) are increasingly used in CABG as the most viable ones having a number of advantages. The impressive long-term patency of the left ITA as a graft to the left anterior descending coronary artery (LITA – LAD) combined with proven long-term viability determined that this conduit has become the gold standard for CABG. However, the use of arterial conduits has expanded beyond ITAs and included the right gastroepiploic artery (GEA), the inferior epigastric artery (IEA), and the radial artery (RA).

INTERNAL THORACIC ARTERY

Based on its long-term patency rates, the ITA has been shown to be an excellent conduit for myocardial revascularization compared with the saphenous vein graft (SVG). The incidence of atherosclerosis in the ITA is low even in patients with severe CAD who underwent CABG [9].

The survival benefits associated with the use of the LITA as a bypass to the LAD were established in the Cleveland Clinic almost 30 years ago [10]. The improved outcome using the ITA is almost certainly due to its superior long-term patency rate of more than 90% within 10 years after surgery [10]. The excellent viability of the ITA can probably be explained by its peculiar morphological features.

The ITA has a discontinuous internal elastic lamina, a relatively thin media and lacks a significant muscular component, which explains its reduced tendency for spasm and development of atherosclerosis [11]. Moreover, compared with all other arterial and venous conduits, it shows increased production of anti-inflammatory and vasoactive molecules [12, 13]. Indeed, endothelial cells of the ITA release more prostacyclin [12] and nitric oxide [13] than those in SVG.

The highest patency rates were documented when the ITA (either *in situ* or as a Y or free graft) was sutured to the left coronary artery and its branches [14]. Poor rates were registered when the ITA was used for right coronary artery bypass (probably due to size discrepancy and disease progression, or to a smaller amount of viable myocardium) [14].

Bilateral use of natural ITA bifurcations (BITA) for myocardial revascularization should be highlighted separately. Only one randomized trial compared outcomes between single ITA and BITA grafting. In the Arterial Revascularization Trial (ART), the primary endpoint – 10-year survival and an interim analysis at 1 year (a "safety" endpoint), reported excellent outcomes with both strategies. Mortality, stroke, myocardial infarction, and repeat revascularization accounted for less than 2.5% in the compared groups [14].

In addition to the ART study, a systematic review of matched cohorts of almost 15,000 CABG patients who received BITA grafts, initiated more than a decade ago, reported significant reduction in the hazard ratio (HR) for mortality [3]. In the past 2 years, two independent meta-analyses have supported this finding, not only in larger cohorts of patients, but also with longer-term follow-up [15, 16].

The major concern with the use of BITA grafts is the increased risk of sternal wound complications and mediastinitis. One of the largest meta-analyses on this issue showed that adding a second ITA to the ITA–LAD bypass graft significantly increases the incidence of sternal complications, and this risk is even higher in diabetes mellitus and in patients with pulmonary diseases [17]. In the ART study, the incidence of sternal wound complications increased from 0.6% in the single ITA group to 1.9% in the BITA group [14].

However, the incidence of serious wound problems can be significantly reduced by judicious patient selection and the choice of harvesting technique. Consideration should be given to avoiding BITA in patients with certain risk factors, especially if they occur simultaneously (diabetes mellitus, obesity, respiratory problems), and in patients receiving steroids or immunosuppressive therapy. Moreover, two systematic reviews both reported that ITA skeletonization, rather than a pedicled harvesting technique, significantly reduces deep sternal wound infections, even in patients with diabetes [17, 18].

RADIAL ARTERY

Introduced in coronary surgery in the 1970s [19], the radial artery (RA) was "rediscovered" in the early 1990s [20]. Concerns over vasospasm due to the muscular nature of the RA wall have been reduced after the demonstration of progressive morphofunctional remodeling of the artery toward an elastomuscular profile after implantation in the coronary circulation [21]. The largest angiographic studies report a RA patency rate of 80 to 90% after 7–10 years of follow-up [22]. According to other authors, 2 years after surgery, the frequency of occlusions and stenosis of *a. radialis* grafts was 35 and 15%, respectively [23].

The severity of stenosis of the target vessel is a key factor in determining RA patency. There is general agreement that the RA should be used only to bypass a vessel with > 70% stenosis, and there is evidence that a 90% stenosis limit ensures an even better RA patency rate, especially in the right coronary artery [24, 25]. The site of proximal anastomosis and the harvesting technique (open and endoscopic) do not affect RA patency rates, whereas skeletonization of the artery can lead to better patency [26].

The RA is an arterial conduit for which there is the most evidence of benefit derived from computed tomography (CT). Results of the RA use have been compared with either SVG or the right internal thoracic artery (RITA) in 4 randomized controlled trials (RCT) [25, 27–29]. A number of meta-analyses that pooled data from these RCTs and large observational studies to compare the RA and the SVG [30–34] with median follow-up time extending beyond the first postoperative year reported significant benefits in terms of graft patency for the RA. The only meta-analysis that included clinical outcomes revealed reduced cardiac death, myocardial infarction, and repeat coronary procedures in addition to a better RA graft patency in the late postoperative period [33].

The RAPCO (Radial Artery Patency and Clinical Outcomes) study revealed no differences in the patency of RA and RITA, but only a slight trend toward better survival without cardiac events for the RA during 6 years of follow-up [29]. The only comparative meta-analysis with clinical endpoints reported comparable mortality, but at the same time reduced cardiac events (myocardial infarction, heart failure, ischemia) for the RA [31]. However, a meta-analysis of angiographic studies showed that the use of RITA was associated with nonsignificant reduction of the absolute risk (by 27%) for late graft occlusion when compared with the RA [34].

Compared with the RITA, the RA appears to be the preferred choice in patients at risk for post-operative sternal complications (diabetes, obesity, chronic obstructive pulmonary disease). Indeed, harvesting of RA is extremely safe and well tolerated even by seriously ill patients [31] and (unlike RITA) does not affect sternal vascularization and healing [35, 36]. Furthermore, a recent Radial Artery Patency Study (RAPS) focusing only on diabetic patients reported a very strong protective effect against graft occlusion with the use of RA [37], making the use of this conduit in diabetics particularly attractive.

Most researchers consider the absence of natural blood supply to the vascular wall through the *vasa vasorum* as one of the main disadvantages of radial grafts. M. Gaudino et al. [38] showed the propensity of radial grafts to spasm. In addition, there is a pronounced proliferative reaction of the vascular wall, leading to stenosis and occlusion of the grafts in the first year after surgery, and the administration of calcium antagonists to prevent *a. radialis* spasm did not improve graft patency in the first year after CABG [39].

GASTROEPIPLOIC ARTERY

J. Pym et al. [40] and H. Suma et al. [41] first independently reported systematic use of the gastroepiploic artery graft for CABG in 1987. Since then, GEA grafts have been widely applied in clinical practice. Very few CABG candidates have contraindications to GEA harvesting [42]; the conduit has a low incidence of severe atherosclerosis [43] and good flow capacity [44].

The biological and physiological profile of the GEA has now been extensively studied [45], and the use of this artery does not increase perioperative risk [46]. The incidence of atherosclerosis in the GEA is rare, but somewhat more common than in ITA [43]. The most favorable target for the *in situ* GEA graft is the distal right coronary artery, but the conduit can also be used for the distal circumflex system. Subocclusive (> 90%) stenosis of the target coronary artery is essential to maximize patency rates and avoid spasm and eventual failure due to chronic competitive coronary flow. This issue is formally recognized in the 2011 ACCF / AHA Guideline for Coronary Artery Bypass, which contraindicates RCA arterial bypass (Class III) in patients with less than critical (i.e., > 90%) stenosis of the native vessel [47].

In one of the largest series of publications on GEA, the cumulative patency rate of the artery was 97.1% at 1 month, 92.3% at 1 year, 85.5% at 5 years, 80.9% at 7 years, and 66.5% at 10 years after surgery [48]. This relatively low patency rate at late periods has improved by using a skeletonized GEA graft only to target vessels with > 90% stenosis. Using this approach, T. Suzuki et al. [49] have reported 97.8%, 94.7%, and 90.2% cumulative patency rates in the early post-operative period and at 5 and 8 years after surgery, respectively.

A number of studies have established that the use of GEA, instead of SVG, to graft the right coronary artery in patients with BITA to the left coronary artery leads to a significant increase in late survival [50, 51]. However, other studies have not confirmed this finding, and a recent meta-analysis of contrast-enhanced coronary angiographies comparing all conduits used in CABG surgery has found that the GEA is associated with the highest risk of functional and complete graft occlusion [34]. Of note, the majority of publications report the use of GEA as a pedicled, rather than a skeletonized graft; skeletonized harvesting of the artery has been shown to significantly improve its patency [49].

MORPHOLOGICAL AND PATHOPHYSIOLOGICAL FACTORS AFFECTING LONG-TERM GRAFT PATENCY

Flow competition is a significant factor affecting arterial morphology and conduit patency. The string sign is an atrophic change in the arterial conduit. This phenomenon occurs due to competitive flow in bypass grafting of only mildly stenosed coronary arteries (CA). It has been shown that the diameter of ITA graft decreases if the stenosis of the native CA is less than critical [52]. In the GEA, patency rates seem to be reduced due to competitive flow. H. Suma et al. [53] reported that the 10-year patency rate of the GEA was 62.5%, and that anastomosis to a less critically stenosed CA was one of the major causes of late graft occlusion. The relationship between the SVG patency and native CA stenosis has also been controversial, but competitive flow may be a negligible factor in SVG graft patency.

Wall shear stress is believed to play an important role in the development of atherosclerosis. T. Shimizu et al. [54] found that shear rates of the ITA were higher compared with the SVG, suggesting that these differences might contribute to the development of degenerative graft disease and affect long-term conduit patency. Indeed, endothelial cells in the ITA release more prostacyclin [12] and nitric oxide [55] than those in the SVG. The effect of flow competition on wall shear stress in a coronary artery bypass conduit is unknown. Greater flow rates and smaller vessel diameter increase wall shear stress.

G. Tinica et al. [56] conducted a study in order to identify morphological and pathophysiological factors associated with long-term patency of grafts used in CABG. The results of CT evaluation of the patency of 340 grafts in 127 patients at 139.78 ± 36.64 months post-CABG were analyzed. Graft patency varied according to the vessel type and target territory. The maximum patency rate was obtained with the RA (80.65%) for the right coronary territory, RITA (92.86%) for the anterolateral territory, and SVG (82.54%) for the circumflex territory.

The LITA – LAD graft occluded in 13 (7.93%) cases, in 7 of them – due to competitive flow. The influence of graft length on patency rates after indexing on height was not significant. The degree of stenosis of the native (bypassed) vessel influenced arterial graft patency rates with an occlusion odds ratio (OR) of 3.02 when anastomosed to target vessels with < 90% stenosis. Target vessel caliber also influenced patency rates with occlusion OR of 2.63 for SVG [95% confidence interval (CI) 1.32–2.98, $p = 0.0041$] and 2.31 for arterial grafts [95% CI 1.53–3.19, $p = 0.0001$] when anastomosed to ≤ 1.5 mm target vessels.

Little is known regarding the transit time flow measurement (TTFM) variables in grafts anastomosed to vessels with chronic total occlusion (CTO). In the study by H. Oshima et al. [57], the TTFM cut-off values were established for detecting graft failure in bypass grafts anastomosed to chronically totally occluded arteries in order to clarify the relationship between early graft failure and the grade of collateral circulation / regional wall motion in the CTO area. A multivariate regression analysis and receiver operating characteristic (ROC) analysis revealed the following predictors of early graft failure: a mean flow (Q_{mean}) value of < 11.5 ml / min for arterial conduits, a pulsatility index (PI) of > 5.85, and akinetic / dyskinetic wall motion in the CTO territory for SVGs.

Thus, morphological parameters such as graft type, target territory, target vessel caliber, and degree of stenosis, are important factors determining long-term graft patency.

RADIOLOGICAL DIAGNOSTIC METHODS FOR ASSESSING THE CORONARY GRAFT CONDITION. RADIONUCLIDE METHODS AND MAGNETIC RESONANCE IMAGING

According to current guidelines, despite evidence showing graft disease in nearly 1 of 5 patients in early post-CABG, cardiac stress testing and anatomical diagnostic procedures are not recommended to assess graft patency in asymptomatic patients within 5 years after CABG [58]. In addition, the hemodynamic significance of graft stenosis cannot always be accurately determined by coronary angiography [59, 60].

Therefore, various diagnostic strategies (invasive or non-invasive) are important for clinical assessment. They can additionally characterize the hemodynamic consequences of the lesion and identify individuals at risk of death and heart failure following successful CABG. In this situation, radiological methods of non-invasive diagnosis, including nuclear medicine techniques, can play an important role.

RADIONUCLIDE METHODS

It is known that stress myocardial perfusion imaging (MPI) with single-photon emission computed tomography (SPECT) is a well-described non-invasive imaging modality for evaluating patients with suspected or established chronic coronary syndrome (CCS). In addition to evaluating regional myocardial perfusion, ECG gating allows for the assessment of left ventricular (LV) function parameters, i.e. LV ejection fraction (EF) and other parameters [61, 62].

Thus, in the study by F. Ortiz et al. [63], patients underwent SPECT–MPI stress testing 1 year after CABG to determine predictors of adverse cardiac outcomes (combination of death and congestive heart failure). It was shown that three separate stress findings predicted the primary outcome: inability to reach stage 3 of the Bruce protocol (OR 7.3, CI 2.4–22.1, $p < 0.001$), LVEF < 45% (OR 4.0, CI 1.1–15.3,

$p = 0.041$), and a moderate-to-large size of stress-induced perfusion defect (OR 2.31, CI 1.1–1.5, $p = 0.04$). These findings are additional and most conclusive among patients who underwent exercise stress test (hazard ratio (HR) 10.6, CI 3.6–30.6, $p < 0.001$).

Severe stress-induced ischemic LV dysfunction can also be detected on SPECT–MPI by nonperfusion markers, such as transient ischemic dilatation (TID) of the LV [64]. The latter is considered another potent marker of severe CAD and predictor of future cardiac events, even when myocardial perfusion appears to be normal [65].

S.S. Gultekin et al. [66] examined 104 patients who had recurrent CAD symptoms after recent coronary revascularization: 62 patients underwent percutaneous transluminal angioplasty (75 arteries) and 42 patients underwent CABG (104 arteries). Follow-up stress SPECT–MPI and repeat coronary angiography were performed in all patients. Parameters of myocardial perfusion and TID were correlated with the presence of significant obstructive CAD (> 70% CA stenosis) (Figure). SPECT–MPI revealed inducible ischemia in 38 patients (36.5%) and TID > 1.20 in 49 patients (47%). Subsequent coronary angiography (22 ± 7 days after SPECT) showed significant obstructive CAD in 44 patients (42%). The sensitivity of detecting obstructive CAD was 61% for SPECT–MPI alone, but increased significantly to 93% with the addition of TID as a diagnostic criterion ($p < 0.0001$).

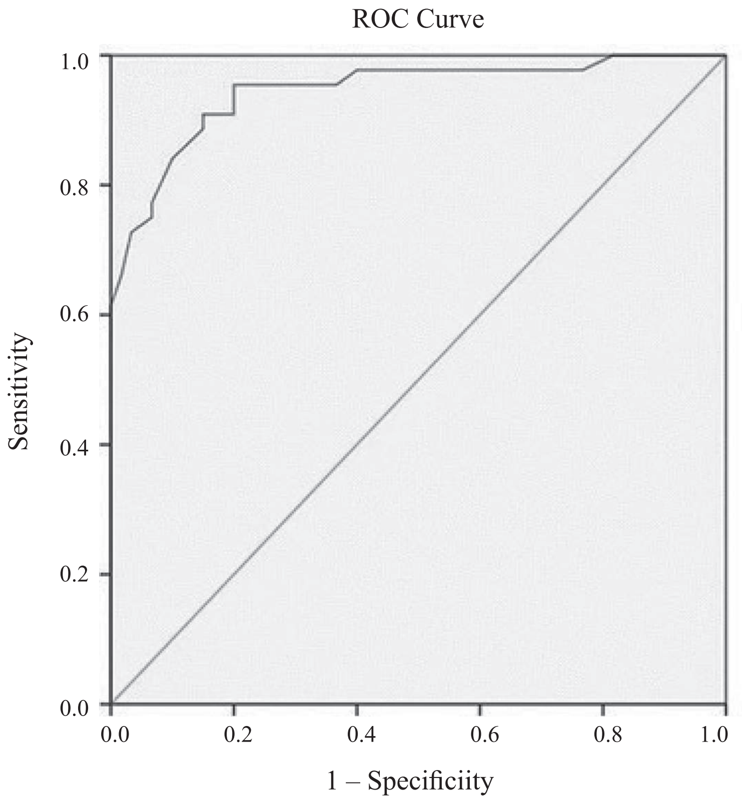

Figure. ROC analysis of LV volume ratio in states of stress and rest in patients with prior coronary revascularization for detection of obstructive (> 70%) CAD [66]

M. Kawasuji et al. [67] compared the flow capacities of ITA and SVG upon exertion by means of radionuclide angiocardiography. 52 patients were divided according to the type of bypass graft performed to the left anterior descending artery: group 1 consisted of 27 patients with the ITA graft, and group 2 included 25 patients with the SVG. SVGs were used to bypass the right and circumflex coronary arteries. Before the surgery, global and regional ejection fractions decreased similarly in both groups with exercise. After the operation, the global ejection fraction measured in groups 1 and 2 increased significantly from 54 ± 2 to 57 ± 2% and from 54 ± 1 to 60 ± 2%, respectively, ejection fraction in the anteroseptal segment – from 29 ± 1 to 32 ± 2% and from 29 ± 1 to 35 ± 1%, respectively, and ejection fraction in the apical segment – from 75 ± 3 to 82 ± 2% and from 77 ± 2 to 86 ± 2%, respectively.

There were no differences in exercise-induced increases in the global and regional ejection fractions between groups 1 and 2. Six patients in group 1 had exercise-induced wall motion abnormalities at the anteroseptal and (or) apical segments. In contrast, patients in group 2 had no exercise-induced wall motion abnormalities at these segments ($p < 0.05$, group 1 vs group 2).

Results of this study show that ITA grafts respond to the increased demand for blood flow during exercise in essentially the same way as SVGs. However, there seems to be a slightly greater potential in patients with the ITA graft when there is inadequate flow, as evidenced by the small group of patients with exercise-induced wall motion abnormalities.

Thus, methods of radionuclide imaging can identify patients at risk of serious cardiovascular complications, including heart failure, for subsequent identification of coronary bypass graft failure using coronary angiography at various times after CABG.

MAGNETIC RESONANCE IMAGING

Cardiovascular magnetic resonance (CMR) is an accurate diagnostic tool for detecting CAD. It offers both functional studies and tissue characterization for quantification of ischemia and myocardial infarction. Multiple studies have demonstrated high diagnostic accuracy of adenosine myocardial perfusion imaging [68–72] with higher spatial resolution compared with radionuclide imaging. However, only some studies have evaluated stress CMR in patients after CABG; at the same time, they demonstrated good sensitivity and specificity in detecting significant (> 50%) stenoses in grafts and native CA [73–75].

In particular, W.L.F. Bedaux et al. [75] assessed the value of CMR-determined graft flow and flow reserve for differentiating significant graft stenosis from hemodynamically insignificant one. 21 patients scheduled for X-ray angiography due to complaints of recurrent chest pain after CABG were included for evaluation of venous grafts ($n = 40$) by CMR. Three-dimensional contrast-enhanced CMR angiography was performed and followed by flow measurements in grafts at rest and during stress-induced hyperemia. Flow reserve was calculated only if the resting flow exceeded 20 ml / min. The analysis was based on four categories defined by X-ray angiography: occluded grafts ($n = 3$), grafts with > 50% stenosis ($n = 19$), grafts with < 50% stenosis with impaired flow ($n = 8$), and grafts with < 50% stenosis and normal flow ($n = 10$).

The CMR angiography demonstrated occlusion of three grafts out of 40. In 9 of 37 grafts, basal blood flow was < 20 ml / min, and all of them demonstrated significant stenosis at X-ray angiography. In grafts with resting flow of > 20 ml / min ($n = 28$), flow reserve significantly differed between grafts without stenosis and grafts with significant stenosis or with impaired flow (2.5 ± 0.7 vs 1.8 ± 0.9, $p = 0.04$). An algorithm combining basal low of < 20 ml / min and graft flow reserve of < 2 had sensitivity and specificity of 78% and 80%, respectively, for detecting grafts with significant stenosis or impaired flow.

In the study by L.P. Salm et al. [76], a direct comparison between SPECT and CMR in evaluating hemodynamic significance of angiographic findings in bypass grafts was performed. In 25 patients, the function of 57 arterial and venous grafts was assessed by angiography, perfusion SPECT, and coronary flow velocity reserve determination using CMR. Based on the results of angiography and SPECT, 4 groups of conduits could be identified: 1) no significant stenosis (< 50%), normal perfusion; 2) significant stenosis (> 50%), abnormal perfusion; 3) significant stenosis, normal perfusion (no hemodynamic significance); and 4) no significant stenosis, abnormal perfusion (suggesting microvascular disease).

A complete evaluation was obtained for 46 grafts. SPECT and CMR provided similar information in 37 of 46 grafts (80%), illustrating good agreement between the methods (kappa = 0.61, $p < 0,001$). Eight grafts supplied blood to areas of the myocardium with scar tissue. When agreement between SPECT and CMR was restricted to grafts without scar tissue, it improved to 84% (kappa = 0.68). Integration of angiography with SPECT categorized 14 lesions in group 1, 23 – in group 2, 6 – in group 3, and

3 – in group 4. The agreement between SPECT and CMR per group was 86%, 78%, 100%, and 33%, respectively.

Thus, the availability and accessibility of such a non-invasive test as CMR imaging, which allows to exclude significant stenosis of grafts and CA, can be a useful screening tool in the follow-up of patients after CABG.

DOPPLER ULTRASOUND

As noted above, higher patency rates of arterial conduits compared with venous grafts have been explained by histologic characteristics, differences in vascular responsiveness to endogenous agonists, and a greater capacity of arterial endothelial cells to secrete endogenous dilators [11, 77, 78]. At the same time, there is little data describing adaptation of these grafts to an increase in myocardial blood flow demand, for example during exercise. Preserved endothelial function in arterial grafts should contribute to good hemodynamic performance of the graft, allowing it to increase its dimensions when the flow increases [77, 79]. It is well known that arterial grafts *in situ* have a smaller diameter and lower initial flow capacity than venous grafts [80], which can limit any increase in blood flow. However, only a few studies are devoted to the comparative hemodynamic assessment of two types of conduits [67, 81, 82].

Quantitative angiography combined with intravascular Doppler velocity analysis, as proposed by J.W. Doucette et al. [83], allows for accurate measurement of the absolute blood flow and can be used to study adaptation of the vessels to an increase in myocardial oxygen demand. Significantly higher peak flow velocity in the distal ITA graft as opposed to the distal SFG has also been reported in studies using pulsed Doppler echocardiography [82]. Thus, flow dynamics apparently differ in these two types of bypass grafts, but no report has examined these differences in detail. There is a number of other non-invasive Doppler echocardiographic assessments of CA bypass grafts [84, 85], but they are limited to examination of the flow at either the proximal [84] or the distal site [85] of the ITA graft.

A recently developed Doppler guide wire (DGW) for phase velocity analysis in grafts can pass through stenotic CA lesions and be used to measure flow velocities distal to the stenosis [86, 87]. With this method, selective cannulation of the bypass graft during cardiac catheterization allows for phasic flow velocities to be recorded within both the graft and the native CA distal to the site of graft insertion.

O. Gurné et al. [88] conducted a study to evaluate *in vivo* the mechanisms by which different coronary bypass grafts react during an increase in flow demand induced by rapid atrial pacing. The authors compared pediculated and free arterial grafts (LITA and inferior epigastric artery (iEGA)) and venous grafts early and later after bypass surgery. Forty three grafts (13 EGA, 15 ITA, 15 SVG) evaluated early (9 ± 3 days) after bypass surgery were compared with 41 other grafts (15 EGA, 11 ITA, 15 SVG) evaluated later after surgery (mean – 23 months, range – from 6 to 168 months) using quantitative angiography and intravascular Doppler velocity analysis during atrial pacing. Controls included 17 normal CAs.

Baseline graft flow tended to be lower late after surgery compared with the early period (41 ± 16 vs 45 ± 21 ml / min, not significant (NS)). Blood flow increased during pacing by 30 ± 16% early after surgery, less than later after surgery (+46 ± 18%, $p < 0.001$) and less than in normal CAs (+54 ± 27%, $p < 0.001$ vs early grafts; NS vs late grafts). There was no difference between venous and arterial grafts. No significant vasodilatation was observed during pacing early after surgery in arterial and venous grafts. Later after surgery, significant vasodilatation was observed only in arterial grafts (ITA and epigastric grafts), from 2.41 ± 0.37 to 2.53 ± 0.41 mm (+5.1% vs baseline $p < 0.001$). Early after surgery and in venous grafts later after surgery, the increase in flow was entirely due to an increase in velocity. In later arterial grafts, the relative contribution of the increase in velocity to the increase in flow during pacing was lower in arterial grafts (70 ± 22%) than in venous grafts (102 ± 11%, $p < 0.001$) and similar to that in normal CAs (68 ± 28%).

The authors concluded that early and later after surgery, arterial grafts and venous grafts both increase their flow similarly during pacing. Early arterial and venous grafts increase their flow only through a rise in velocity. Later after surgery, arterial grafts act as physiological conduits and increase their flow in the same way as normal CAs, through an increase in velocity and caliber determined by the endothelium.

As mentioned above, the ITA and GEA graft diameter has been shown to decrease when the native CA stenosis is less than critical [52, 53]. This phenomenon is due to competitive flow in mildly stenosed CAs. In the study by T. Shimizu et al. [54], the shear stress as a significant factor affecting graft patency was compared between the arterial conduit and SVG after CABG. In 101 patients, 40 ITAs, 27 GEAs, and 34 SVGs were examined using DGW during postoperative angiography. The graft flow volume and shear stress were calculated from velocity and diameter data. The study grafts were classified according to the grade of native CA stenosis: group L had 50 to 75% stenosis, and group H had more than 75% stenosis. Group H consisted of 25 ITAs, 17 GEAs, and 21 SVGs, while group L consisted of 15 ITAs, 10 GEAs, and 13 SVGs.

In group H, graft flow volume did not significantly differ among the ITA (34 ± 11 ml / min), GEA (36 ± 16 ml / min), and SVG (41 ± 15 ml / min), while graft shear stress significantly (ITA vs GEA, p = 0,0001; GEA vs SVG, p = 0.01) differed among the ITA (16.0 ± 4.8 dyn / cm^2), GEA (9.1 ± 3.2 dyn / cm^2), and SVG (4.8 ± 1.6 dyn / cm^2). In group L, flow volume was lower ($p < 0.001$) in the ITA (18 ± 6 ml / min) and the GEA (13 ± 8 ml / min) than in the SVG (35 ± 16 ml / min), and shear stress was significantly ($p < 0.001$) greater in the ITA (13.7 ± ± 4.9 dyn / cm^2) than in the GEA (5.6 ± 2.0 dyn / cm^2) or the SVG (4.6 ± 2.0 dyn / cm^2). According to the authors, these data suggest that the superior shear stress of the ITA is maintained despite the reduction of flow volume due to flow competition. Lower shear stress of the GEA in intermediate stenosis may be associated with the development of conduit failure.

There are reports that the postoperative capacity of ITA – LAD grafts is limited compared with that of SVG [67]. Therefore, the aim of study by T. Akasaka et al. [89] was to assess flow dynamics and flow capacities of these conduits to the left anterior descending coronary artery using DGW.

Phasic flow velocity recordings were obtained in the midportion of the bypass graft and within the native LAD artery using a 0.018-in. (0.046-cm) 12-MHz DGW in 53 patients: 27 patients with an ITA graft (16 with a new graft assessed at 1 month postoperatively and 11 patients with an old graft assessed at 1 year) and 26 patients with a SVG (13 patients with a new graft assessed at 1 month postoperatively and 13 patients with an old graft assessed at 1 year). All patients were studied at baseline rest and during hyperemia induced by intravenous infusion of dipyridamole (0.56 mg / kg of body weight) for 4 min.

In the left anterior descending artery itself, systolic and diastolic peak velocities, the time average of the instantaneous spectral peak velocity (time-averaged peak velocity), vessel diameter, and the calculated flow volume did not differ significantly among the four graft groups. The time-averaged peak velocity was significantly greater for new than for old arterial grafts or for new or old venous grafts (27 ± 9 vs 19 ± 6, 11 ± 5, and 12 ± 6 cm / s, respectively, $p < 0.01$). However, since the diameter of new arterial grafts was significantly smaller than that of the other three grafts (2.4 ± 0.1 vs 2.9 ± 0.2 [$p < 0.05$], 3.6 ± 0.6 [$p < 0.01$], and 3.4 ± 0.5 mm [$p < 0.01$], respectively), there was no difference in the calculated flow volumes at rest (62 ± 17 vs 58 ± 15, 61 ± 18, and 58 ± 19 ml / min, respectively, NS) between new arterial grafts and the other grafts.

Although the maximum time-averaged peak velocity during hyperemia was significantly greater in new than in old arterial grafts or new or old venous grafts (47 ± 17 vs 40 ± 7, 31 ± 8, and 34 ± 12 cm / s, respectively, $p < 0.01$), the flow reserve of new arterial grafts was significantly smaller than that of the other three groups (1.8 ± 0.3 vs 2.6 ± 0.3, 2.8 ± 0.5, and 3.0 ± 0.6, respectively, $p < 0.01$), since the baseline time-averaged peak velocity of these new grafts was far greater than that of the other groups.

Thus, ITA graft flow early after the surgery is characterized by higher rest velocity compared with venous graft flow. This high velocity maintains flow volume at baseline values in compensation for the smaller diameter. Although flow reserve does not differ significantly between new and old venous grafts, the reserve for ITA grafts is significantly reduced soon after bypass surgery. This restricted flow capacity improves in the late postoperative period because of an increase in the diameter and a decrease in flow velocity compared with baseline levels.

CONCLUSION

X-ray angiography is considered to be a standard procedure for assessing patency of coronary grafts, because it provides excellent visualization of the graft and quantitative information about the size of the lumen and the presence of obstruction and, thus, provides indications for revascularization. However, the hemodynamic significance of stenosis cannot be accurately determined by coronary angiogram. Therefore, the availability and high information value of other diagnostic radiology methods can be a useful screening tool at any stage of patient monitoring after CABG.

REFERENCES

1. Centers for disease control and prevention. Prevalence of coronary heart disease – United States, 2006–2010. M*MWR*. 2011;60(40):1377–1381.
2. Center for Disease Control and Prevention, National Center for Health Statistics. Underlying Cause of Death 1999–2013 on CDC WONDER Online Database, released 2015. Data are from the Multiple Cause of Death Files, 1999–2013, as compiled from data provided by the 57 vita statistics jurisdictions through the Vital Statistics Cooperative Program.
3. Taggart D.P., D'Amico R., Altman D.G. Effect of arterial revascularisation on survival: a systematic review of studies comparing bilateral and single internal mammary arteries. *Lancet*. 2001;358(9285):870–875. DOI: 10.1016/S0140-6736(01)06069-X.
4. Shahian D.M., O'Brien S.M., Sheng S., Grover F.L., Mayer J.E., Jacobs J.P. et al. Predictors of long-term survival after coronary artery bypass grafting surgery: results from the Society of Thoracic Surgeons Adult Cardiac Surgery Database (the ASCERT study). *Circulation.* 2012;125(12):1491–1500. DOI: 10.1161/CIRCULATIONAHA.111.066902.
5. Wu C., Camacho F.T., Wechsler A.S., Lahey S., Culliford A.T., Jordan D. et al. Risk score for predicting long-term mortality after coronary artery bypass graft surgery. *Circulation.* 2012;125(20): 2423–2430. DOI: 10.1161/CIRCULATIONAHA.111.055939.
6. Moreyra A.E., Deng Y., Wilson A.C., Cosgrove N.M., Kostis W.J., Kostis J.B. Incidence and trends of heart failure admissions after coronary artery bypass grafting surgery. *European Journal of Heart Failure.* 2013;15(1):46–53. DOI: 10.1093/eurjhf/hfs154.
7. Lopes R.D., Mehta R.H., Hafley G.E., Williams J.B., Mack M.J., Peterson E.D. et al. Relationship between vein graft failure and subsequent clinical outcomes after coronary artery bypass surgery. *Circulation.* 2012;125(6):749–756. DOI: 10.1161/CIRCULATIONAHA.111.040311.
8. Murad H. Saphenous vein graft stenosis. *Arq. Bras. Cardiol.* 2020;115(3):545–546. DOI: 10.36660/abc.20200633.
9. Goldman S., Zadina K., Moritz T., Ovitt Th., Sethi G., Copeland J.G. et al. Long-term patency of saphenous vein and left internal mammary artery grafts after coronary artery bypass surgery: results from a department of veterans affairs cooperative study. *J. Am. Coll. Cardiol.* 2004;44(11):2149–2156. DOI: 10.1016/j.jacc.2004.08.064.
10. Loop F.D., Lytle B.W., Cosgrove D.M., Stewart R.W., Goormastic M., Williams G.W. et al. Influence of the internal-mammary-artery graft on 10-year survival and other cardiac events. *N. Engl. J. Med.* 1986;314(1):1–6. DOI: 10.1056/NEJM198601023140101.
11. Otsuka F., Yahagi K., Sakakura K., Virmani R. Why is the mammary artery so special and what protects it from atherosclerosis? *Ann. Cardiothorac. Surg.* 2013;2(4):519–526. DOI: 10.3978/j.issn.2225-319X.2013.07.06.
12. Bonatti J., Dichtl W., Dworzak E.A., Antretter H., Unger F., Puschendorf B. et al. Stimulated prostacyclin release by conduits used for coronary artery bypass grafting. *Thorac. Cardiovasc. Surg.* 1998 46(2):59–62. DOI: 10.1055/s-2007-1010190.
13. Broeders M.A., Doevendans P.A., Maessen J.G., van Gorsel E., Egbrink M.G., Daemen M.J. et al. The human internal thoracic artery releases more nitric oxide in response to vascular endothelial growth factor than the human saphenous vein. *J. Thorac. Cardiovasc. Surg.* 2001;122(2):305–309. DOI: 10.1067/mtc.2001.113602.
14. Taggart D.P., Altman D.G., Gray A.M., Lees B., Nugara F., Yu L. et al. Randomized trial to compare bilateral vs. single internal mammary coronary artery bypass grafting: 1-year results of the Arterial Revascularisation Trial (ART). *Eur. Heart J.* 2010;31(20):2470–2481. DOI: 10.1093/eurheartj/ehq318.
15. Weiss A.J., Zhao S., Tian D.H., Taggart D.P., Yan T.D. A meta-analysis comparing bilateral internal mammary artery with left internal mammary artery for coronary artery bypass grafting. *Ann. Cardiothorac. Surg.* 2013;2(4):390–400. DOI: 10.3978/j.issn.2225-319X.2013.07.16.
16. Yi G., Shine B., Rehman S.M., Altman D.G., Taggart D.P. Effect of bilateral internal mammary artery on long-term survival: a meta-analysis approach. *Circulation.* 2014;130(7):539–545. DOI: 10.1161/CIRCULATIONAHA.113.004255.
17. Dai C., Lu Z., Zhu H., Xue S., Lian F. Bilateral internal mammary artery grafting and risk of sternal wound infection: evidence from observational studies. *Ann. Thorac. Surg.* 2013;95(6):1938–1945. DOI: 10.1016/j.athoracsur.2012.12.038.
18. Deo S.V., Shah I.K., Dunlay S.M., Erwin P.J., Locker C., Altarabsheh S.E. et al. Bilateral internal thoracic artery harvest and deep sternal wound infection in diabetic patients. *Ann. Thorac. Surg.* 2013;95(3):862–869. DOI: 10.1016/j.athoracsur.2012.11.068.
19. Carpentier A., Guermonprez J.L., Deloche A., Frechette C., DuBost C. The aorta-to-coronary radial artery bypass graft: a technique avoiding pathological changes in grafts. *Ann. Thorac. Surg.* 1973;16(2):111–121. DOI: 10.1016/s0003-4975(10)65825-0.

20. Acar C., Jebara V.A., Portoghese M., Beyssen B., Pagny J.Y., Grare P. et al. Revival of the radial artery for coronary artery bypass grafting. *Ann. Thorac. Surg*. 1992;54(4):652–659. DOI: 10.1016/0003-4975(92)91007-v.
21. Gaudino M., Prati F., Caradonna E., Trani C., Burzotta F., Schiavoni G. et al. Implantation in the coronary circulation induces morphofunctional transformation of radial grafts from muscular to elastomuscular. *Circulation.* 2005;112(Suppl.9):1208–1211. DOI: 10.1161/CIRCULATIONAHA.104.512889.
22. Tatoulis J., Buxton B.F., Fuller J.A., Meswani M., Theodore S., Powar N., Wynne R. Longterm patency of 1108 radial arterial-coronary angiograms over 10 years. *Ann. Thorac. Surg.* 2009;88(1):23–29. DOI: 10.1016/j.athoracsur.2009.03.086.
23. Khot U., Friedman D., Petterson G., Smedira N.G., Li J., Ellis S.G. Radial artery bypass grafts have an in-creased occurrence of angiographically severe stenosis and occlusion compared with left internal mammary arteries and saphenous vein grafts. *Circulation.* 2004;109(17):2086–2091. DOI: 10.1161/01.CIR.0000127570.20508.5C.
24. Deb S., Cohen E.A., Singh S.K., Une D., Laupacis A., Fremes S.E. Radial artery and saphenous vein patency more than 5 years after coronary artery bypass surgery: results from RAPS (Radial Artery Patency Study). *J. Am. Coll. Cardiol.* 2012;60(1):28–35. DOI: 10.1016/j.jacc.2012.03.037.
25. Gaudino M., Alessandrini F., Pragliola C., Cellini C., Glieca F., Luciani N. et al. Effect of target artery location and severity of stenosis on mid-term patency of aorta-anastomosed vs. internal thoracic artery anastomosed radial artery grafts. *Eur. J. Cardiothorac. Surg.* 2004;25(3):424–428. DOI: 10.1016/j.ejcts.2003.11.027.
26. Gaudino M., Crea F., Cammertoni F., Mazza A., Toesca A., Massetti M. Technical issues in the use of the radial artery as a coronary artery bypass conduit. *Ann. Thorac. Surg.* 2014;98(6):2247–2254. DOI: 10.1016/j.athoracsur.2014.07.039.
27. Goldman S., Sethi G.K., Holman W., Thai H., et al. Radial artery grafts vs saphenous vein grafts in coronary artery bypass surgery: a randomized trial. *JAMA*. 2011;305(2):167–174. DOI: 10.1001/jama.2010.1976.
28. Collins P., Webb C.M., Chong C.F., Moat N.E. Radial artery versus saphenous vein patency randomized trial: five year angiographic follow-up. *Circulation.* 2008;117(22):2859–2864. DOI: 10.1161/CIRCULATIONAHA.107.736215.
29. Hayward P.A., Buxton B.F. Mid-term results of the Radial Artery Patency and Clinical Outcomes randomized trial. Ann. Cardiothorac. Surg. 2013;2(4):458–466. DOI: 10.3978/j.issn.2225-319X.2013.07.18.
30. Benedetto U., Angeloni E., Refice S., Sinatra R. Radial artery versus saphenous vein graft patency: meta-analysis of randomized controlled trials. *J. Thorac. Cardiovasc. Surg.* 2010;139(1):229–231. DOI: 10.1016/j.jtcvs.2009.05.038.
31. Hu X., Zhao Q. Systematic comparison of the effectiveness of radial artery and saphenous vein or right internal thoracic artery coronary bypass grafts in non-left anterior descending coronary arteries. *J. Zhejiang Univ. Sci. B.* 2011;12(4):273–279. DOI: 10.1631/jzus.B1000241.
32. Cao C., Manganas C., Horton M., Bannon P., Munkholm-Larsen S., Ang Su.C. et al. Angiographic outcomes of radial artery versus saphenous vein in coronary artery bypass graft surgery: a meta-analysis of randomized controlled trials. *J. Thorac. Cardiovasc. Surg.* 2013;146(2):255–261. DOI: 10.1016/j.jtcvs.2012.07.014.
33. Zhang H., Wang Z.W., Wu H.B., Hu X.P., Zhou Z., Xu P. Radial artery graft vs. saphenous vein graft for coronary artery bypass surgery: which conduit offers better efficacy? *Herz.* 2014;39(4):458–465. DOI: 10.1007/s00059-013-3848-5.
34. Benedetto U., Raja S.G., Albanese A., Amrani M., Biondi-Zoccai G., Frati G. Searching for the second best graft for coronary artery bypass surgery: a network meta-analysis of randomized controlled trials. *Eur. J. Cardiothorac. Surg.* 2015;47(1):59–65. DOI: 10.1093/ejcts/ezu111.
35. Tranbaugh R.F., Dimitrova K.R., Lucido D.J., Hoffman D.M., Dincheva G.R., Geller C.M. et al. The second best arterial graft: a propensity analysis of the radial artery versus the free right internal thoracic artery to bypass the circumflex coronary artery. *J. Thorac. Cardiovasc. Surg.* 2014;147(1):133–140. DOI: 10.1016/j.jtcvs.2013.08.040.
36. Hoffmann D.M., Dimitrova K.R., Lucido D.J., Dincheva G.R., Geller C.M., Balaram S.K. et al. Optimal conduit for diabetic patients: propensity analysis of radial and right internal thoracic arteries. *Ann. Thorac. Surg.* 2014;98(1):30–36. DOI: 10.1016/j.athoracsur.2014.03.044.
37. Deb S., Singh S.K., Moussa F., Tsubota H., Une D., Kiss A. et al. The long-term impact of diabetes on graft patency after coronary artery bypass grafting surgery: a substudy of the multicenter Radial Artery Patency Study. *J. Thorac. Cardiovasc. Surg.* 2014;148(4):1246–1253. DOI: 10.1016/j.jtcvs.2014.06.057.
38. Gaudino M., Glieca F., Luciani N., Alessandrini F., Possati G. Clinical and angiographic effects of chronic calcium channel blocker therapy continued beyong first postoperative year in patients with radial artery grafts: results of a prospective randomized investigation. *Circulation.* 2001;104(12Suppl.1): 64. DOI: 10.1161/hc37t1.094819.
39. Patel A., Asopa S., Dunning J. Should patients with radial artery conduit have post-operative calcium channel blockers? *Interact. Cardiovasc. Thorac. Surg.* 2006;5(3):251–257. DOI: 10.1510/icvts.2006.129262.
40. Pym J., Brown P.M., Charrette E.J., Parker J.O., West R.O. Gastroepiploic-coronary anastomosis: a viable alternative bypass graft. *J. Thorac. Cardiovasc. Surg.* 1987;94(2):256–259.
41. Suma H., Fukumoto H., Takeuchi A. Coronary artery bypass grafting by utilizing in situ right gastroepiploic artery: basic study and clinical application. *Ann. Thorac. Surg.* 1987;44(4):394–397. DOI: 10.1016/s0003-4975(10)63799-x.
42. Saito T., Suma H., Terada Y., Wanibuchi Y., Fukuda S., Furuta S. Availability of the in situ right gastroepiploic artery for coronary artery bypass. *Ann. Thorac. Surg.* 1992;53(2):266–268. DOI: 10.1016/0003-4975(92)91330-c.

43. Suma H., Takanashi R. Arteriosclerosis of the gastroepiploic and internal thoracic arteries. *Ann. Thorac. Surg.* 1990;50(3):413–416. DOI: 10.1016/0003-4975(90)90485-o.
44. Ochiai M., Ohno M., Taguchi J., Hara K., Suma H., Isshiki T. et al. of human gastroepiploic arteries to vasoactive substances: comparison with responses of internal mammary arteries and saphenous veins. *J. Thorac. Cardiovasc. Surg*. 1992;104(2):453–458.
45. Takayama T., Suma H., Wanibuchi Y., Tohda E., Marsunaka T., Yamashita S. Physiological and pharmacological responses of arterial graft flow after coronary artery bypass grafting measured with an implantable ultrasonic Doppler miniprobe. *Circulation*. 1992;86(Suppl.5):217–223.
46. Suma H., Wanibuchi Y., Furuta S., Takeuchi A. Does use of gastroepiploic artery graft increase surgical risk? *J. Thorac. Cardiovasc. Surg.* 1991;101(1):121–125.
47. Hillis D.L., Smith P.K., Anderson J.L., Bittl J.A. et al. 2011 ACCF/AHA guideline for coronary artery bypass graft surgery: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines: developed in collaboration with the American Association for Thoracic Surgery, Society of Cardiovascular Anesthesiologists, and Society of Thoracic Surgeons. *J. Am. Coll. Cardiol.* 2011;58(24):e123–210. DOI: 10.1016/j.jacc.2011.08.009.
48. Suma H., Tanabe H., Takahashi A., Horii T., Isomura T., Hirose H. et al. Twenty years experience with the gastroepiploic artery graft for CABG. Circulation. 2007;116(Suppl.11):188–191. DOI: 10.1161/CIRCULATIONAHA.106.678813.
49. Suzuki T., Asai T., Nota H., Kuroyanagi S., Kinoshita T., Takashima N. et al. Early and long-term patency of in situ skeletonized gastroepiploic artery after off-pump coronary artery bypass graft surgery. *Ann. Thorac. Surg.* 2013;96(1):90–95. DOI: 10.1016/j.athoracsur.2013.04.018.
50. Glineur D., D'hoore W., Price J., Dorméus S., de Kerchove L., Dion R. et al. Survival benefit of multiple arterial grafting in a 25-year single-institutional experience: the importance of the third arterial graft. *Eur. J. Cardiothorac. Surg.* 2012;42(2):284–290. DOI: 10.1093/ejcts/ezr302.
51. Suzuki T., Asai T., Matsubayashi K., Kambara A., Kinoshita T., Takashima N. et al. In off-pump surgery, skeletonized gastroepiploic artery is superior to saphenous vein in patients with bilateral internal thoracic arterial grafts. *Ann. Thorac. Surg.* 2011;91(4):1159–1164. DOI: 10.1016/j.athoracsur.2010.12.031.
52. Shimizu T., Hirayama T., Suesada H., Ikeda K., Ito S., Ishimaru S. Effect of flow competition on internal thoracic artery graft: postoperative velocimetric and angiographic study. *J. Thorac. Cardiovasc. Surg.* 2000;120(3):459–465. DOI: 10.1067/mtc.2000.108166.
53. Suma H., Isomura T., Horii T., Sato T. Late angiographic result of using the right gastroepiploic artery as a graft. *J. Thorac. Cardiovasc. Surg.* 2000;120(3):496–498. DOI: 10.1067/mtc.2000.108690.
54. Shimizu T., Ito Sh., Kikuchi Y., Misaka M., Hirayama T., Ishimaru Sh. et al. Arterial conduit shear stress following bypass grafting for intermediate coronary artery stenosis: a comparative study with saphenous vein grafts. *European Journal of Cardio-thoracic Surgery*. 2004;25(4):578–584. DOI: 10.1016/j.ejcts.2003.12.039.
55. Broeders M.A., Doevendans P.A., Maessen J.G., van Gorsel E., Egbrink M.G., Daemen M.J. et al. The human internal thoracic artery releases more nitric oxide in response to vascular endothelial growth factor than the human saphenous vein. *J. Thorac. Cardiovasc. Surg.* 2001;122(2):305–309. DOI: 10.1067/mtc.2001.113602.
56. Tinica G., Chisto R.O., Enache M., Constantin M.M.L., Ciocoiu M., Furnica C. Long-term graft patency after coronary artery bypass grafting: Effects of morphological and pathophysiological factors. *Anatol. J. Cardiol.* 2018;20(5):275–282. DOI: 10.14744/AnatolJCardiol.2018.51447.
57. Oshimaa H., Tokudaa Y., Arakia Y., Ishiib H., Muroharab T., Ozakic Y. et al. Predictors of early graft failure after coronary artery bypass grafting for chronic total occlusion. *Interactive Cardiovasc. and Thoracic Surgery*. 2016;23(1):142–149. DOI: 10.1093/icvts/ivw084.
58. Wolk M.J., Bailey S.R., Doherty J.U., Douglas P.S., Hendel R.C., Kramer C.M. et al. American College of Cardiology Foundation Appropriate Use Criteria Task Force. ACCF/AHA/ASE/ASNC/HFSA/HRS/ SCAI/SCCT/SCMR/STS 2013 multimodality appropriate use criteria for the detection and risk assessment of stable ischemic heart disease: a report of the American College of Cardiology Foundation Appropriate Use Criteria Task Force, American Heart Association, American Society of Echocardiography, American Society of Nuclear Cardiology, Heart Failure Society of America, Heart Rhythm Society, Society for Cardiovascular Angiography and Interventions, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, and Society of Thoracic Surgeons. *J. Am. Coll. Cardiol.* 2014;63(4):380–406. DOI: 10.1016/j.jacc.2013.11.009.
59. White C.W., Wright C.B., Doty D.B., Hiratza L.F., Eastham C.L., Harrison D.G. et al. Does visual interpretation of the coronary arteriogram predict the physiologic importance of a coronary stenosis? *N. Engl. J. Med.* 1984;310(13):819–824. DOI: 10.1056/NEJM198403293101304.
60. Topol E.J., Nissen S.E. Our preoccupation with coronary luminology. The dissociation between clinical and angiographic findings in ischemic heart disease. *Circulation.* 1995;92(8):2333–2342. DOI: 10.1161/01.cir.92.8.2333.
61. Hesse B., Tägil K., Cuocolo A., Anagnostopoulos C., Bardiés M., Bax J. et al. EANM/ESC procedural guidelines for myocardial perfusion imaging in nuclear cardiology. *Eur. J. Nucl. Med. Mol. Imaging.* 2005;32(7):855–897. DOI: 10.1007/s00259-005-1779-y.
62. Strauss H.W., Miller D.D., Wittry M.D., Cerqueira M.D., Garcia E.V., Iskandrian A.S. et al. Procedure guideline for myocardial perfusion imaging 3.3. *J. Nucl. Med. Technol.* 2008;36(3):155–161. DOI: 10.2967/jnmt.108.056465.
63. Ortiz F., Mbai M., Adabag S., Garcia S., Nguyen J., Goldman S. et al. Utility of nuclear stress imaging in predicting long-term outcomes one-year post CABG surgery. *J. Nucl.*

Cardiol. 2018;27(6):1970–1978. DOI: 10.1007/s12350-018-01469-y.
64. Xu Y., Arsanjani R., Clond M., Hyun M., Lemley M. Jr., Fish M. et al. Transient ischemic dilation for coronary artery disease in quantitative analysis of same-day sestamibi myocardial perfusion SPECT. *J. Nucl. Cardiol.* 2012;19(3):465–473. DOI: 10.1007/s12350-012-9527-8.
65. Abidov A., Bax J.J., Hayes S.W., Hachamovitch R., Cohen I., Gerlach J. et al. Transient ischemic dilation ratio of the left ventricle is a significant predictor of future cardiac events in patients with otherwise normal myocardial perfusion SPECT. *J. Am. Coll. Cardiol.* 2003;42(10):1818–1825. DOI: 10.1016/j.jacc.2003.07.010.
66. Gultekin S.S., Sadic M., Bilgin M., Koca G., Acikel S., Yeter E. et al. The value of transient ischemic dilation for detecting restenosis after coronary artery revascularization. *Journal of Nuclear Cardiology*. 2018;25(2):586–592. DOI: 10.1007/s12350-016-0607-z.
67. Kawasuji M., Tsujiguchi H., Tedoriya T., Taki J., Iwa T. Evaluation of postoperative flow capacity of internal mammary artery. *J. Thorac. Cardiovasc. Surg*. 1990;99(4):696–702.
68. Nandalur K.R., Dwamena B.A., Choudhri A.F., Nandalur M.R., Carlos R.C. Diagnostic performance of stress cardiac magnetic resonance imaging in the detection of coronary artery disease: a meta-analysis. *J. Am. Coll. Cardiol.* 2007;50(14):1343–1353. DOI: 10.1016/j.jacc.2007.06.030
69. Chih S., Macdonald P.S., Feneley M.P., Law M., Graham R.M., McCrohon J.A. Reproducibility of adenosine stress cardiovascular magnetic resonance in multi-vessel symptomatic coronary artery disease. *J. Cardiovasc. Magn. Reson.* 2010;12(1):42. DOI: 10.1186/1532-429X-12-42.
70. De Jong M.C., Genders T.S., van Geuns R.J., Moelker A., Hunink M.G. Diagnostic performance of stress myocardial perfusion imaging for coronary artery disease: a systematic review and meta-analysis. *Eur. Radiol.* 2012;22(9):1881–1895. DOI: 10.1007/s00330-012-2434-1.
71. Kwong R.Y., Ge Y., Steel K., Bingham S., Abdullah S., Fujikura K. et al. Cardiac magnetic resonance stress perfusion imaging for evaluation of patients with chest pain. *J. Am. Coll. Cardiol.* 2019;74(14):1741–1755. DOI: 10.1016/j.jacc.2019.07.074.
72. Van Assen M., Kuijpers D.J., Schwitter J. MRI perfusion in patients with stable chest-pain. *Br. J. Radiol.* 2020;93(1113):20190881. DOI: 10.1259/bjr.20190881.
73. Klein C., Nagel E., Gebker R., Kelle S., Schnackenburg B., Graf K. et al. Magnetic resonance adenosine perfusion imaging in patients after coronary artery bypass graft surgery. *JACC*. 2009;2(4):437–445. DOI: 10.1016/j.jcmg.2008.12.016.
74. Bernhardt P., Spiess J., Levenson B., Pilz G., Hofling B., Hombach V. et al. Combined assessment of myocardial perfusion and late gadolinium enhancement in patients after percutaneous coronary intervention or bypass grafts: a multicenter study of an integrated cardiovascular magnetic resonance protocol. *JACC.* 2009;2(11):1292–1300. DOI: 10.1016/j.jcmg.2009.05.011.
75. Bedaux W.L.F., Hofman M.B.M., Vyt S.L.A., Bronzwaer J.G.F., Visser C.A., van Rossum A.C. Assessment of coronary artery bypass graft disease using cardiovascular magnetic resonance determination of flow reserve. *J. Am. Coll. Cardiol.* 2002;40(10):1848–1855. DOI: 10.1016/s0735-1097(02)02491-9.
76. Salm L.P., Bax J.J., Vliegen H.W., Langerak S.E., Dibbets P., Jukema J.W. et al. Functional significance of stenoses in coronary artery bypass grafts. evaluation by single-photon emission computed tomography perfusion imaging, cardiovascular magnetic resonance, and angiography. *J. Am. Coll. Cardiol.* 2004;44(9):1877–1882. DOI: 10.1016/j.jacc.2004.07.048.
77. Hanet C., Schroeder E., Michel X., Cosyns J., Dion R., Verhelst R. et al. Flow-mediated vasomotor response to tachycardia of the human internal mammary artery and saphenous vein grafts late following bypass surgery. *Circulation.* 1991;84(5Suppl.):268–274.
78. Gurné O., Chenu P., Polidori C., Louagie Y., Buche M., Haxhe J.P. et al. Functional evaluation of internal mammary artery bypass grafts in the early and late postoperative period. *J. Am. Coll. Cardiol.* 1995;25(5):1120–1128. DOI: 10.1016/0735-1097(94)00538-2.
79. Gurné O., Chenu P., Buche M., Jamart J., Louagie Y., Eucher P. et al. Flow-mediated vasodilation during pacing of the free epigastric artery bypass graft early and late postoperatively. *J. Am. Coll. Cardiol.* 1996;27(2):415–420. DOI: 10.1016/0735-1097(95)00453-x.
80. Loop F.D., Thomas J.D. Hypoperfusion after arterial bypass grafting. *Ann. Thorac. Surg.* 1993;56(4):812–813. DOI: 10.1016/0003-4975(93)90337-h.
81. Fujiwara T., Kajiya F., Kanazawa S., Matsuoka S., Wada Y., Hiramatsu O. et al. Comparison of blood-flow velocity waveforms in different coronary artery bypass grafts: sequential saphenous vein grafts and internal mammary artery grafts. *Circulation.* 1988;78(5Pt1):1210–1217. DOI: 10.1161/01.cir.78.5.1210.
82. Fusejima K., Takahara Y., Sudo Y., Murayama H., Masuda Y., Inagaki Y. Comparison of coronary hemodynamics in patients with internal mammary artery and saphenous vein coronary, artery bypass grafts: a noninvasive approach using combined two-dimensional and Doppler echocardiography. *J. Am. Coll. Cardiol.* 1990; 15(1):131–139. DOI: 10.1016/0735-1097(90)90188-u.
83. Doucette J.W., Corl D., Payne H., Flynn A.E., Goto M., Nassi M. et al. Validation of a Doppler guidewire for intravascular measurement of coronary artery flow velocity. *Circulation.* 1992;85(5):1899–1911. DOI: 10.1161/01.cir.85.5.1899.
84. De Bono D.P., Samani N.J., Spyt T.J., Hartshorne T., Thrush A.J., Evans D.H. Transcutaneous ultrasound measurement of blood-flow in internal mammary artery to coronary artery grafts. *Lancet*.1992;339(8790):379–381. DOI: 10.1016/0140-6736(92)90076-f.
85. Takayama T., Suma H., Wanibuchi Y., Tohda E., Matsunaka T., Yamashita S. Physiological and pharmacological responses of arterial graft flow after coronary artery bypass grafting measured with an implantable ultrasonic Doppler miniprobe. *Circulation.* 1992;86(5Suppl.): 217–223.

86. Ofili E., Kern M.J., Tatinei S., Deligonul U., Aguirre F., Serota H. et al. Detection of coronary collateral flow by a Doppler-tipped guide wire during coronary angioplasty. *Am. Heart J.* 1991;122(1Pt):221–225. DOI: 10.1016/0002-8703(91)90780-l.
87. Segal J., Kern M.J., Scott N.A., King S.B. 3rd, Doucette J.W., Heuser R.R. et al. Alterations of phasic coronary artery flow velocity in humans during percutaneous coronary angioplasty. *J. Am. Coll. Cardiol.* 1992;20(2):276–286. DOI: 10.1016/0735-1097(92)90091-z.
88. Gurné O., Chenu P., Buche M., Louagie Y., Eucher P., Marchandise B. et al. Adaptive mechanisms of arterial and venous coronary bypass grafts to an increase in flow demand. *Heart.* 1999;82(3):336–342. DOI: 10.1136/hrt.82.3.336.
89. Akasaka T., Yoshikawa J., Yoshida K., Maeda K., Hozumi T., Nasu M. et al. Flow capacity of internal mammary artery grafts: early restriction and later improvement assessed by doppler guide wire. **C**omparison with saphenous vein grafts. *J. Am. Coll. Cardiol.* 1995;25(3):640–47. DOI: 10.1016/0735-1097(94)00448-Y.

Authors information

Vesnina Zhaneta V. – Dr. Sci. (Med.), Head of the Laboratory for Radionuclide Research Methods, Cardiology Research Institute, Tomsk NRMC, Tomsk, zhvesnina@mail.ru, https://orcid.org/0000-0002-9238-6814

Grakova Elena V. – Dr. Sci. (Med.), Leading Researcher, Department of Myocardial Pathology, Cardiology Research Institute, Tomsk NRMC, Tomsk, gev@cardio-tomsk.ru, https://orcid.org/0000-0003-4019-3735

(✉) **Vesnina Zhaneta V.,** zhvesnina@mail.ru

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