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REVIEW ARTICLE

Intraoperative graft assessment and imaging of native coronary arteries

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Abstract
The evaluation of native coronary arteries in cardiac surgery represents a useful tool to detect coronary artery stenosis, identify the target artery, and choose the best anastomotic site. Intraoperative graft assessment is a fundamental step of coronary artery bypass grafting. It is able to reduce graft failure related to technical error, improving both short- and long-term outcome of patients submitted to surgical myocardial revascularization. Herein procedures of graft assessment are described, reporting their strengths and limitations.

Keywords Intraoperative graft verification · Transit-time flow measurement · High-resolution epicardial ultrasonography

High resolution imaging for native coronary arteries evaluation

The use of high resolution ultrasonography (HR-ECUS) in the evaluation of native coronary arteries is a well-known method from the 1980s when for the first time. Sahn et al. used HR-ECUS in coronary evaluation in patients submitted to valvular surgery with negative angiography (normal coronaries) and in patients with severe coronary disease [1].

They demonstrated a high correlation between angiographic findings and intraoperative imaging with an R-value of 0.91. They were the first to report the potential use of this method to select the best site for coronary artery bypass graft (CABG) anastomosis and to evaluate the presence of severe stenosis in chronic vessel occlusion where angiography gives less information. The dimension of the probe used by Sahn et al. was 7 × 6 × 5 cm, and the frequency of the signal was 9 MHz.

In 1986, McPherson et al. validated the use of epicardial echocardiography for the measurement of wall thickness and vessel lumen of coronary artery measured with ultrasonography in animal studies and autopsy compared with histologic measurements [2]. They demonstrated a good correlation between the two methods suggesting that epicardial coronary echography could be a useful tool for in vivo coronary artery evaluation in patients.

One of the major issues in the evaluation of coronary arteries is the dimension of the probe that should be put on the epicardial surface of the heart. In 2008, the introduction of a smaller probe with a wide range of frequencies from 8 up to 18 MHz for HR-ECUS (Medistim, Oslo, Norway) extended the usefulness of this method in the field of coronary surgery simplifying the evaluation of the coronary arteries, arterial graft, aorta, and coronary anastomosis.

Concerning the role of HR-ECUS in the evaluation of native coronary arteries, we started to use it in 2009, and we reported three cases of HR-ECUS guided coronary revascularization on the left anterior descending artery (LAD) in patients submitted to surgery without preoperative angiography for different reasons [3]. In all three cases, we decided to revascularize the LAD because we demonstrated a severe stenosis in the proximal part of the LAD. In these patients' transit-time flow measurement (TTFM) of the coronary graft confirmed the presence of a severe stenosis in the native vessel.

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With the improved confidence with the method, we routinely perform native coronary arteries scan from the left main coronary artery to the proximal part of the LAD and circumflex (LCx) arteries.

Another use of HR-ECUS is the localization of the best anastomotic point or the vessel itself in case of intramyocardial course especially in off-pump CABG.

We routinely use imaging in off-pump CABG to measure the lumen of the vessel at the level of the anastomotic site after stabilization to choose the dimension of the shunt that should be used (Fig. 1).

Technique for left coronary artery evaluation (Video 1)

The left main can be easily scanned from its origin to the bifurcation and the proximal part of the LAD and LCx. The probe should be held between the index and middle finger and passed between the left auricle and the pulmonary trunk to reach the transverse sinus and the top of left main coronary artery. To obtain a more reliable imaging, the pericardial sac should be filled with warm water.

The left main can be scanned in longitudinal and cross section views. Scrolling the probe distally in short axis view at the level of the bifurcation, the LAD will be on the right and the LCx on the left. If there is a ramus intermedius, it will appear between the LAD and LCx (Fig. 2).

With the use of 2-D and color flow mapping (CFM), imaging the extent of plaque, lumen reduction, and flow acceleration can be easily assessed. Moreover, there is the chance to measure the diameter of the residual lumen calculating the percentage of stenosis. To avoid over or underestimation of the stenosis, it is important to not compress the vessel below the probe.

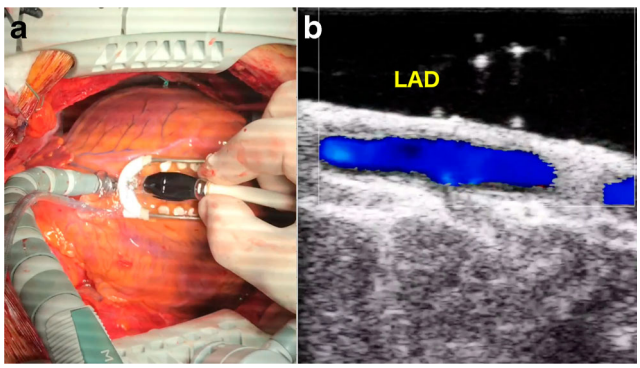

Fig. 1 **a** HR-ECUS probe on the LAD. **b** Imaging of the anastomotic site on the LAD

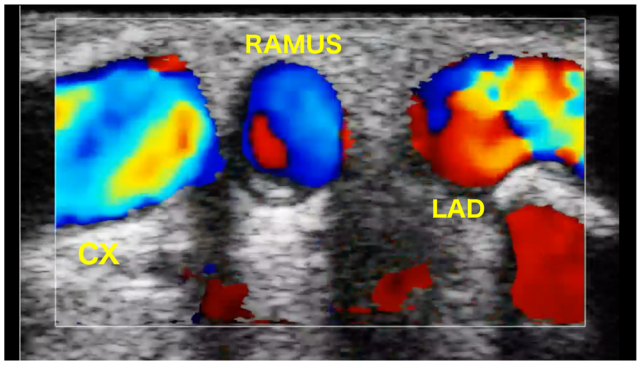

Fig. 2 Trifurcation of the left main stem. Short axis view

Technique for right coronary artery evaluation

The probe should be positioned at the level of the origin of the right coronary artery from the aorta moving towards the right atrio-ventricular groove overtaking the acute margin of the heart up to the crux cordis. The right coronary artery can be viewed in cross section and longitudinal scans with or without color flow mapping.

Theory of intraoperative graft assessment with TTFM and HR-ECUS

From the beginning of CABG surgery, the need to check the good function of the saphenous vein grafts was immediately recognized. In fact, Grondin et al. in 1971 published their experience using electromagnetic flow measurement to verify intraoperatively saphenous vein grafts [4]. They demonstrated that a flow of less than 48 ml/min was associated with a lower rate of patency. Electromagnetic flow measurement has many drawbacks (hematocrit values, need of calibration, vessel caliber, motion artifacts, and vessel heating). In the 1990s, the introduction of TTFM and the need for confirmation of efficacy of off-pump CABG compared to on-pump procedures renewed the interest for intraoperative graft assessment. TTFM technology is based on the Doppler principle. The probe is made of two piezoelectric crystals oriented at 45° that emit two signals, one in the same direction of flow and another one opposite of flow. A reflector on the opposite site of the vessel reflects the signals towards the piezoelectric crystals with a time shifting proportional to the amount of flow. The main parameters are mean graft flow (MGF), the pulsatility index (PI) obtained as a ratio of the difference between the maximum and minimum flow and the mean flow; the diastolic filling (DF), corresponding to the amount of

Table 1 Reported cut-offs for TTFM parameters in different experiences

Author	Cut-off values	Sensitivity (%)	Specificity (%)
Kim et al. [8]	MGF < 15 ml/min—PI > 3 (LCA) or PI > 5 (RCA) PI > 5	96	77
Di Giammarco et al. [7]	MGF ≤ 15 ml/min—PI ≥ 3	94	61
Tokuda, et al. [9]	MGF ≤ 15 ml/min—PI ≥ 5.1 (LCA)	26	98
	MGF ≤ 20 ml/min—PI ≥ 4.7 (RCA)	60	98
Kieser et al. [10]	PI > 5	-	-

MGF, mean graft flow; *PI*, pulsatility index; *LCA*, left coronary artery; *RCA*, right coronary artery

diastolic perfusion of coronary arteries; and the backward flow (BF), the amount of retrograde flow in the graft coming from native coronary artery. TTFM, compared to electromagnetic flow meter, is not influenced by hematocrit and vessel caliber and does not need any calibration. Its validation was obtained by comparing the amount of flow measured with exsanguination and TTFM. The R-values are of 0.99 for both the saphenous vein and the internal thoracic artery [5]. After the first experiences of flow trace interpretation to detect technical problems of the graft, the cut-off of the main TTFM parameters was reported [6]. Our group found that a MGF equal or less than 15 ml/min and a PI equal or higher than 3 along with a BF higher than 3 or equal to 0 were predictors of graft failure in the first postoperative year [7]. Other groups identified other cut-offs (Table 1) [8–10]. The main drawback of TTFM cut-off is the low sensitivity that will lead to a high number of false positive grafts (grafts with suboptimal cut-off but without any anastomotic error). In order to increase the sensitivity of the intraoperative graft verification, from 2009, the introduction in the clinical practice of HR-ECUS gives the chance to assess with imaging the anastomosis and the body of the graft, excluding so any anastomotic stenosis or dissection of the grafts and reducing the need of intraoperative graft revision. This new tool increased the diagnostic accuracy of the combined procedure adding a morphological assessment to the functional one achieved with TTFM [11].

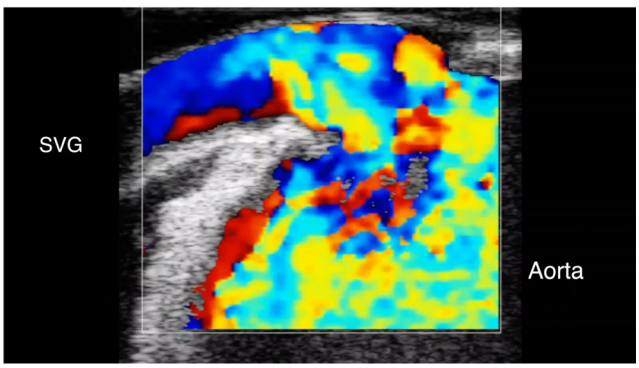

Fig. 3 Proximal anastomosis of a saphenous vein graft to the aorta

Procedural aspects of intraoperative graft verification

In off-pump procedure, the scan of the anastomosis should be done during stabilization of the vessel to avoid motion artifacts and obtain good quality imaging. In on-pump CABG, for free-graft, the scan should be performed by gently injecting the conduit with blood. The proximal anastomosis itself should be scanned (Fig. 3). In case of arterial conduit, the temporary opening of the graft permits to obtain adequate imaging. The anastomosis should be checked in both long- and cross-sectional views with 2-D and color flow mapping (Fig. 4). To obtain good acoustic coupling, a sterile gel can be used or the pericardium can be filled with saline solution. For TTFM, the flow meter should be connected to patient's EKG and blood pressure in order to obtain reliable measurements, especially for the parameter DF. The measurement is obtained after the completion of anastomosis with the heart in normal position in off-pump surgery, after aortic cross-clamp release in on-pump surgery and weaning from cardiopulmonary bypass. The last measurement should be done after heparin reversal before chest closure either in off- or on-pump CABG. The technical aspects to obtain reliable TTFM measurements are related to avoid any compression of the graft with a too small a probe (use probe with adequate caliber), obtain good acoustic coupling using the gel, measure as close as possible to the anastomosis, and avoid vessel kinking.

Moreover, it is important to wait till the red line indicating the stabilization of the measurement is completely

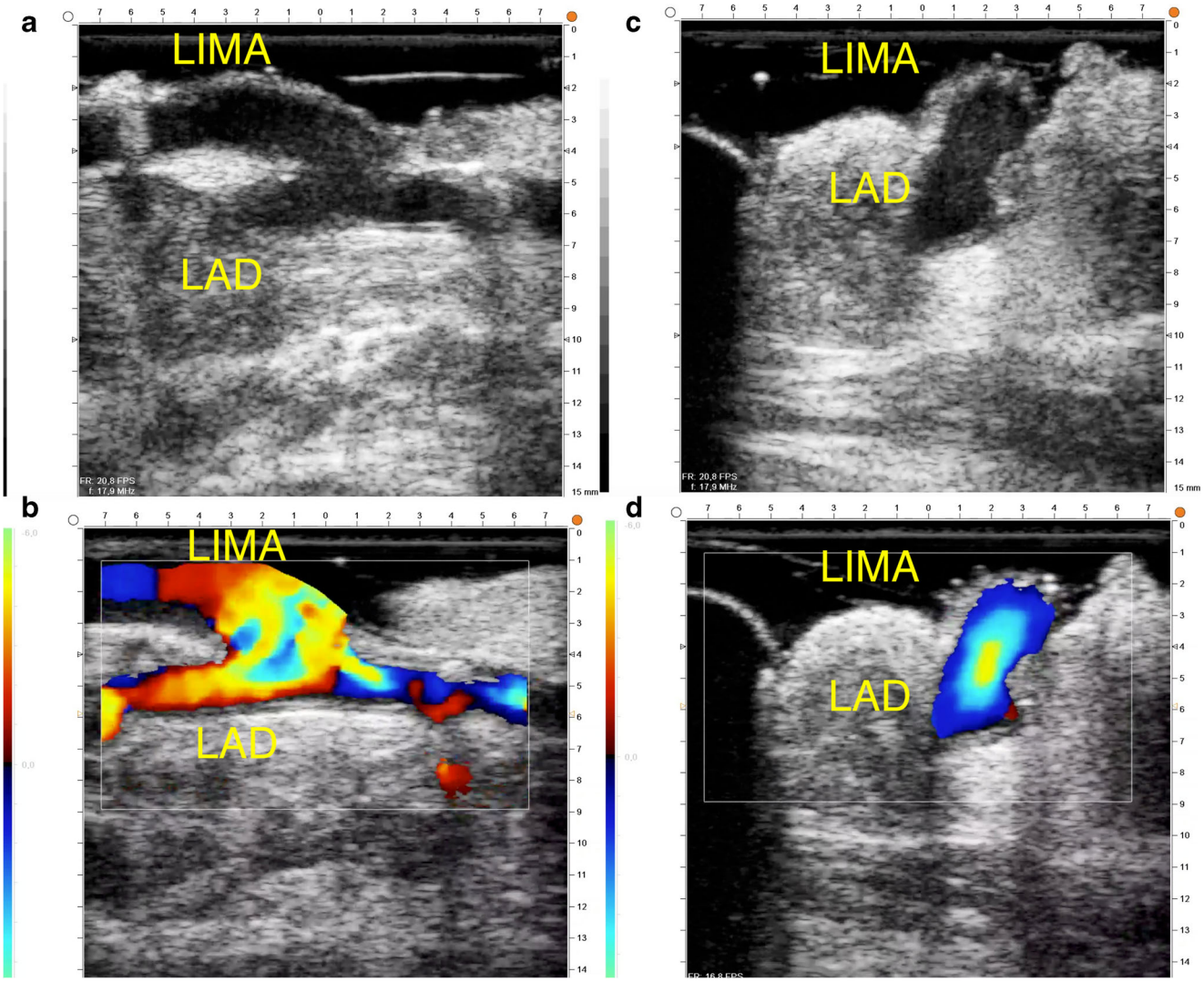

Fig. 4 HR-ECUS of a left internal mammary artery to LAD. **a** 2-D longitudinal view. **b** CFM longitudinal view. **c** 2-D short axis view. **d** CFM short axis view

flat and that the filter of the machine is settled at 20 Hz. The dobutamine test simulates an intraoperative stress test in order to check the graft flow reserve and predicts the fate of the graft as shown in the following section [12] (Fig. 5). A bolus of 20 mcg/kg of body weight is administered, and the TTFM measurements repeated as previously described.

The flow chart of intraoperative graft assessment

We developed a flow chart of intraoperative verification to guide the surgeon through the entire procedure of graft assessment [13]. The first step of intraoperative graft verification procedure is the check with HR-ECUS of the arterial conduit. Subsequently, after the completion of the distal anastomosis, the second step is the morphological verification with HR-ECUS. In case of stenosis, the anastomosis should be redone immediately. The third step is the functional verification of the graft with TTFM. Repeated measures should be obtained as indicated in the previous section. There are three possible scenarios. The first (low MGF, low PI, and BF between 0 and 3) indicates a graft with a poor run-off. If the parameters will improve after dobutamine test, we can argue that the graft will have a good fate, conversely the risk of graft failure is high (Fig. 4). The second scenario (low MGF, high PI, and high BF) is a situation of competition of flow. This situation can occur in case of a graft put on a vessel with a moderate stenosis or more commonly in case of composite arterial conduits when the stenoses of the native vessels are unbalanced. If the parameter values will improve after dobutamine test, the

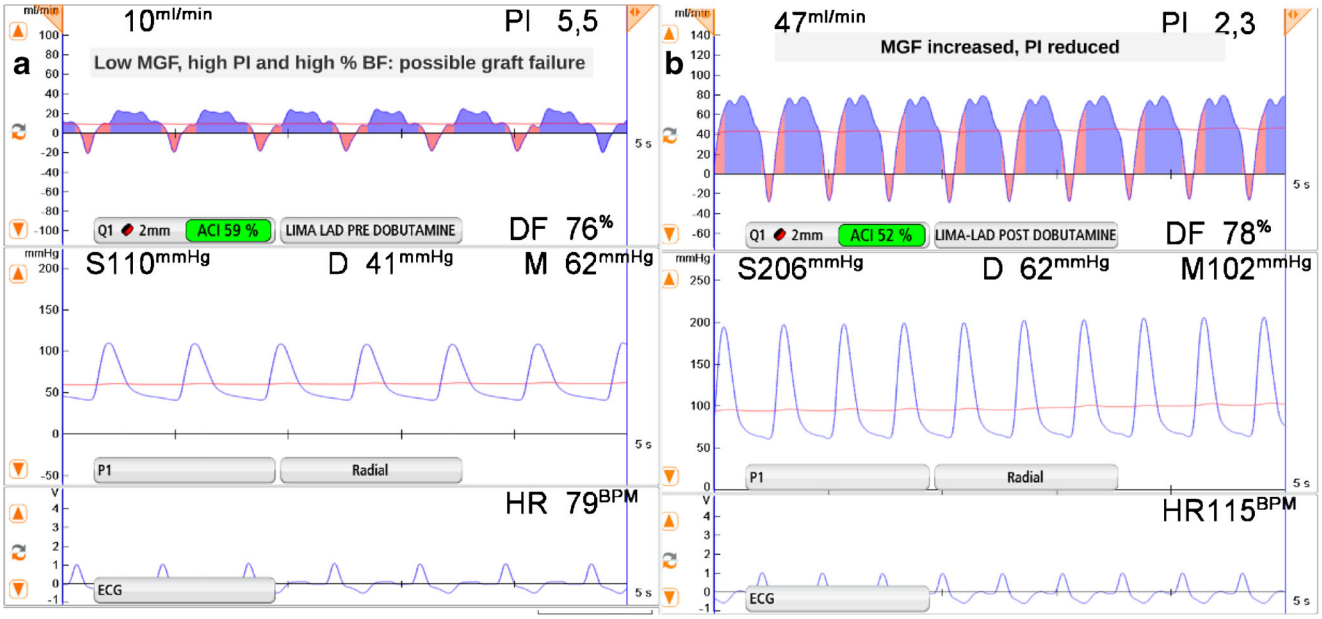

Fig. 5 Dobutamine test in case of graft suboptimal flow (see details in the text)

graft will have a good prognosis, conversely especially for composite grafts; conduit configuration should be rearranged.

The third scenario is characterized by normal TTFM parameters (MGF > 15, PI < 3, and BF between 0 and 3) conferring to the graft a good chance to be patent at mid-term follow-up.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent and ethical committee approval Not applicable as the manuscript is a review paper.

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