Assessment of Patency of Coronary Artery Bypass Grafts Using Segmented K-space Breath-hold Cine Cardiovascular Magnetic Resonance Imaging: A Clinical Feasibility Study

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Purpose : The efficacy of magnetic resonance imaging for evaluating coronary artery disease has been reported. In this study, we evaluated the usefulness of breath-hold segmented K-space cine MR imaging for evaluating the patency of coronary artery bypass grafts (CABG).

Materials and Methods : Thirty eight patients with a total of 92 CABGs (36 internal thoracic arteries and 56 saphenous vein grafts) were evaluated using segmented K-space cardiac-gated fast gradient echo sequence (2D-FASTCARD) MR imaging. MR magnitude images were evaluated from the hard copies by two independent observers. A graft was defined as patent if it was seen as a bright small round area on at least two consecutive images throughout the cardiac cycle at a position consistent with the expected location for that graft.

Results : MR images were obtained successfully for 23 patients (61%). The sagittal planes were most helpful in visualizing the cross-section of sapheneous vein bypass graft to left circumflex artery branch, whereas the transverse planes were used for identification of internal mammary artery grafts to left anterior descending coronary artery or its branch and identification of saphenous vein grafts to right coronary artery. Forty five grafts were visible using this MR technique, while the grafts were not visible on seven saphenous vein grafts and two internal mammary artery grafts. In two patients showing symptoms of myocardial ischemia, one or two bypass grafts were not visible. Imaging, perpendicular plane to a CABG was important to visualize the flow inside the CABG with maximum sensitivity.

Conclusion : Evaluation of patency of the bypass graft was clinically feasible by 2D-FASTCARD MR imaging, whereas any invisible bypass grafts should be further studied by contrast-enhanced MR angiography or by conventional angiography for confirmation of abnormalities.

Index words : Segmented K-space imaging,
Coronary bypass graft,
Flow analysis,
CABG patency,
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The development of a rapid and noninvasive technique for assessing coronary artery bypass graft (CABG) patency is of major clinical importance because the increasing number of patients are undergoing CABG surgery. To date, the gold standard for evaluating graft patency in CABG patients is coronary angiography, an invasive and costly procedure that is not risk-free. Previous studies have demonstrated the high sensitivity and moderate specificity of conventional magnetic resonance (MR) spin echo and gradient echo techniques in the evaluation of patency of CABG (1–7). However, calcifications, metal clips, thickened pericardium, and small pericardial collections of fluid can mimic the signal void of flowing blood. In contrast to the signal void of flowing blood, flowing blood on gradient echo images is depicted as a bright signal. Although spin echo and gradient echo images give noninvasive, qualitative information regarding graft flow, quantitative information is not obtained. Cine gradient echo MR imaging would be performed perpendicular to the graft at selected levels that best display the graft location and allow measurement of flow by means of phase velocity mapping. Cine images that display flowing blood through multiple phases of the cardiac cycle are an useful adjunct to conventional MR techniques (7–8). Both conventional gradient echo sequences and phase-contrast techniques are suitable when gated to the cardiac cycle to remove cardiac motion artifacts, but the acquisition time to acquire a full cine sequence is 3-4 minutes. In order to image CABG, blurring caused by respiratory motion should be avoided. In addition, adequate spatial resolution should be provided to identify small saphenous vein and internal mammary artery grafts in CABG patients. Segmented K-space cardiac sequences were described by Atkinson and Edelman (9) and allow 12-18 phases of the cardiac cycle to be acquired in a single breath-hold using prospective cardiac gating, eliminating both respiratory and cardiac motion artifacts (10–12).

In this study, we investigated the usefulness and the limitation of current methodology for evaluating the patency of CABG.

Materials and Methods

Patients

The 38 patients (20 men and 18 woman) who received CABG were evaluated by using MR imaging for the graft patency. The mean age was 58.3 years. The 38 patients had a total of 92 grafts (36 internal thoracic artery and 56 saphenous vein grafts). Angiographic confirmation of the grafts was not obtained, because these patients did not have any symptoms suggesting graft stenosis. MR-CABG were performed in 2-6 months after CABG operation.

Surgical Techniques

Coronary artery bypass surgery was done under conventional cardiopulmonary bypass with mild systemic hypothermia (32-34°C) and cardioplegia or off-pump state (OPCABG). Proximal anastomosis of saphenous vein graft for right coronary artery graft was made directly anterior or to the lateral side of the aorta, whereas openings for left-side grafts were made on the left lateral side. Subsequently, right grafts course vertically and inferiorly, parallel to the atrioventricular (AV) groove, to reach the right coronary artery or posterior descending artery.

When internal mammary arteries were used as grafts, they were dissected away from the posterior surface of the upper seven ribs and separated before branching into musculophrenic and superior epigastric artery. They were used to bypass the left anterior descending artery. Graft was anastomosed to coronary artery by end-to-side or sequential patterns.

MR imaging

MR imaging was performed on a 1.5 T SIGNA HORIZON scanner (GE Medical Systems, Milwaukee, WI). All patients except one were imaged in prone position with a bodiflex coil centered at the midsternal level.

The grafts were identified on sagittal and transverse multilevel breath-hold cardiac gated fast GRE scout views.

The pulse sequence consists of a segmented K-space ECG-gated fast gradient recalled echo acquisition with a relatively short TR (14 ms) combined with a very short TE (7.5 ms) and flip angle of 12°. The TR and TE are usually the minimum values achievable by the MR gradient system, so that these parameters may be automatically set by the system software 2D-FASTCARD. These acquisition parameters result in saturation of background and stationary tissues, whereas inflowing blood with unsaturated spins has a higher signal intensity (flow-related enhancement).

During each heart beat, the R-R interval of the cardiac cycle is divided into multiple cine frames typically of 20- to 80-msec duration. Only a portion of K-space is then collected over the duration of each cine frame. The number of lines of K-space acquired over the duration of a cine frame is the number of views per segment (VPS). VPS multiplied by TR equals the duration of the cine frame. When multiple lines of K-space are collected per R-R interval, the imaging time decreases by a factor of VPS. VPS in this study was four, therefore the completion of 160 phase-encoding steps of K-space with VPS=8 would require 20 R-R intervals (heart beats). The total acquisition time is thus determined by the patient' s heart rate (typically 13–18 seconds).

Slice thickness was 7 mm, interslice gap was 1 mm, acquisition matrix was 160×256, the field of view (FOV) was 30×30 cm, and spatial resolution was 1.9×1.2×7 mm^3. Flow compensation was used to remove pulsatile artifacts.

Imaging analysis

Reconstructed magnitude images had a pixel dimension of approximately 0.9×0.9 mm. The lumen of the graft covered mostly 2 or 3 pixel dimensions. MR magnitude images were evaluated from the hard copies by two independent observers. A third consensus reading was undertaken after the individual evaluations. Only the surgical history regarding the number and type of grafts was disclosed to the radiologists before image evaluation. A graft was defined as patent if it was seen as a bright blood flow signal (a small round area) on at least two consecutive images throughtout the cardiac cycle from the proximal anastomosis site or cardiac epicardial surface. A graft was judged inconclusive if the investigator was not sure about its patency and if no consensus could be obtained between the three observers.

Results

Diagnostic MR images were obtained for all patients without respiratory, cardiac, or pulsatile artifacts. Patent saphenous vein and internal mammary artery grafts appeared as rounded bright structures when they were coursing perpendicular to the imaging plane.

Graft patency

The sagittal partitions were most helpful in following the course of saphenous vein bypass graft (SVBG) to left circumflex artery (LCx), whereas the axial images were routinely assessed for identification of internal mammary artery grafts and SVBG graft to RCA. The proximal segments of the grafts were identified from the typical sites of the aortic anastomosis. The graft with the most cephalic origin from the aorta and coursing laterally from the distal main pulmonary artery or the left pulmonary artery was considered to anastomose with diagonal or marginal branches of LCx. The graft with the most caudal origin from the aorta coursing next to the right atrium or atrioventricular groove was considered to anastomose with the RCA or posterior descending artery (PDA, RCA region).

Patent left internal mammary artery (LIMA) graft to left anterior descending (LAD) artery or patent LAD itself by graft was visualized on axial images that were nearly perpendicular to the graft and LAD region. There were three invisible LIMA-LAD grafts in this study. LIMA grafts were not seen mostly in the superior transverse plane of heart, but observed without difficulty in the more inferior plane close to the position of anatomosis to LAD, where it presented bright spot due to patent flow inside LAD.

Classification of all patients into a couple of groups with different shunting configuration of the bypass grafts is summarized in Table 1. This grouping was helpful to identify the position and patency of each graft in the obtained MR images on the basis of presence or absence of a graft by comparison of each group. Forty-five grafts were visible, while nine grafts were not. Description of shunting configuration and typical results for each type are presented in following figures.

1) Type 1: SVBG-LCx branch, SVBG-RCA or PDA, LIMA-LAD grafts

Twenty three grafts were visible, while six grafts were not. All three SVBG-RCA grafts were clearly visible but two of six SVBG-PDA grafts were not. In case those patients with invisible SVBG-PDA grafts did not show any symptom of obstructed grafts, there was a possibility of incorrectly selected imaging slice with respect to the grafts. In these cases, we obtained oblique slices which are orthogonal to the long axes of grafts.

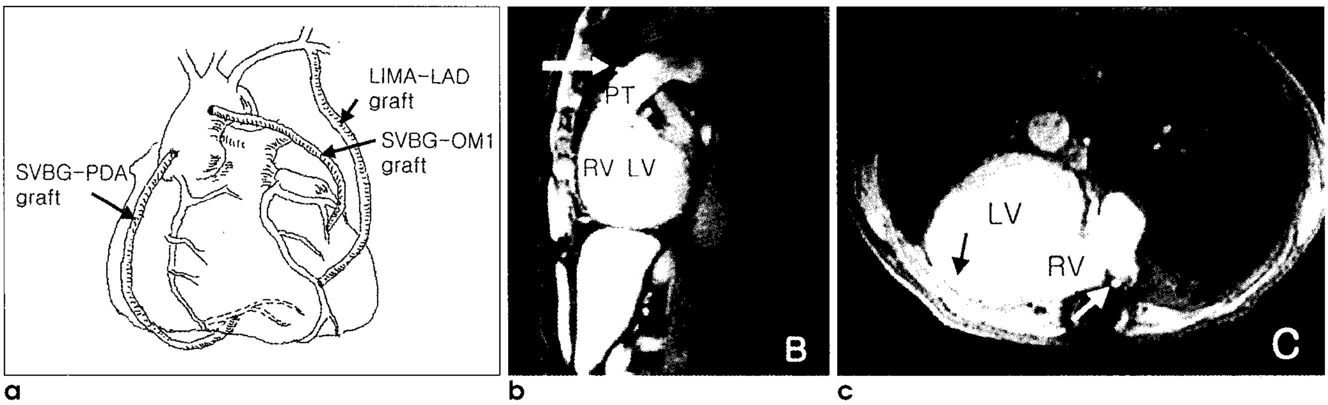
In one patient, the imaging slice gap was too thick (in our first trial: 10 mm slice and 7 mm gap) to catch proper perpendicular image to the graft flow. There was a patient showing a symptom of myocardial ischermia, whose SVBG-LCx graft was not seen, whereas two other grafts were visible. This patient was in supine position, since he had some difficulty in prone position. In comparison with the image obtained in prone position, it may be difficult to exclude motional artifacts in supine position due to the coupled physiological motion inside the chest, resulting in image blurring. Another patient showing a severe symptom (chest pain during exercise) at three months after MR examination presented a potentially obstructed and stenotic bypass graft. The patient had four bypass grafts: at the time of MR imaging (two months after surgery), two bypass grafts, LIMA-LAD and SVBG-PDA, were seen clearly, while a SVBG-D1 was invisible and a SVBG-OM1 was seen vaguely as demonstrated in Figure 3.

2) Type 2: only LIMA-LAD graft

In Figure 4, the graft of LIMA to LAD is seen clearly, and intact normal flowing of RCA is also visible near the AV groove of right side. The LIMA to LAD graft was apparent in three consecutive imaging slices, presumably showing a part of patent LAD itself by the graft which was proximal to the LAD.

Table 1. Visibility of the Grafts According to Operation Types and Anastomosed Arteries

		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	total
SVBG-RCA	Visible	3						3
	Invisible						1	1
SVBG-PDA	Visible	5		1			1	7
	Invisible	1				1		2
SVBG-LCx	Visible	10			9			19
	Invisible	1		1	1			3
LIMA-LAD	Visible	8	1		7	1		17
	Invisible	1			1			2
SVBG-LAD	Visible			1				1
	Invisible							



a b c

Fig. 1. Schematic presentation of the typical location and course of saphenous vein coronary bypass grafts (to RCA region and LCx branch) and left internal mammary artery coronary bypass graft (to LAD) in type 1 configuration (**a**). Breath-hold gated fast GE image perpendicular to LCx graft in a sagittal plane at the level of the pulmonary trunk (PT) shows LCx graft as indicated by white block arrow (LV, left ventricle; MPA, main pulmonary artery; RV, right ventricle). (**b**) Transverse fast GE image above the level of four chambers shows the cross-section of an RCA graft and LIMA-LAD graft (**c**).

3) Type 3: SVBG-LCx branch, SVBG-PDA, and SVBG-LAD grafts

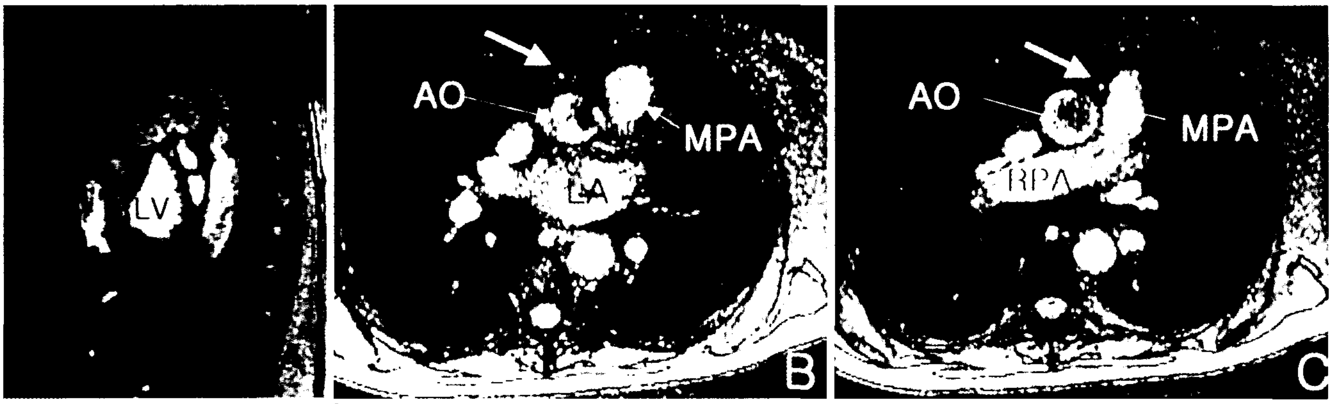
There was only one patient with this type of graft surgery. The SVBGs coursing to the LAD territory had a more proximal origin than the graft to the PDA, and were seen in sagittal as well as transverse plane as shown in Figure 5. The SVBGs to the LCx, which were anastomosed most superiorly to the anterior aspect of the ascending aorta was not seen clearly. The graft to the PDA was seen in a transverse plane.

4) Type 4: SVBG-OM1 and D1 (LCx branches) and LIMA-LAD grafts

LIMA-LAD graft was clearly seen in several consecutive transverse planes. The patent LAD itself was more distally seen in the just AV surface, while the patent LIMA-LAD graft was apparent adjacent the AV surface as demonstrated in Figure 6. Two SVBG to LCx branches were well visualized in a sagittal plane. In the patient of Figure 6, PDA was severely calcified, and the diameter was less than 1 mm before CABG surgery. Subsequently intact RCA was not seen clearly in the AV groove. In a number of patients with this kind of graft type, seven grafts (four SVBG-LCx and three LIMA-LAD grafts) were not seen. In Figure 6-c we can compare the appearances of visible and invisible LIMA-LAD grafts.

5) Type 5: LIMA-LAD and SVBG-PDA or -RCA grafts

In case RCA was not accessible due to severe calcification the bypass graft was anastomosed to PDA. There was only one patient with this type of graft configuration. Both grafts were seen quite vaguely in transverse plane as shown in Figure 7, while intact



a b c

Fig. 2. LCx graft in a sagittal plane was not seen in a patient with a symptom in a supine position (**a**), while the cross sections of RCA graft (**b**) and LIMA-LAD graft (**c**) were visible in each transverse plane as indicated by white block arrows.

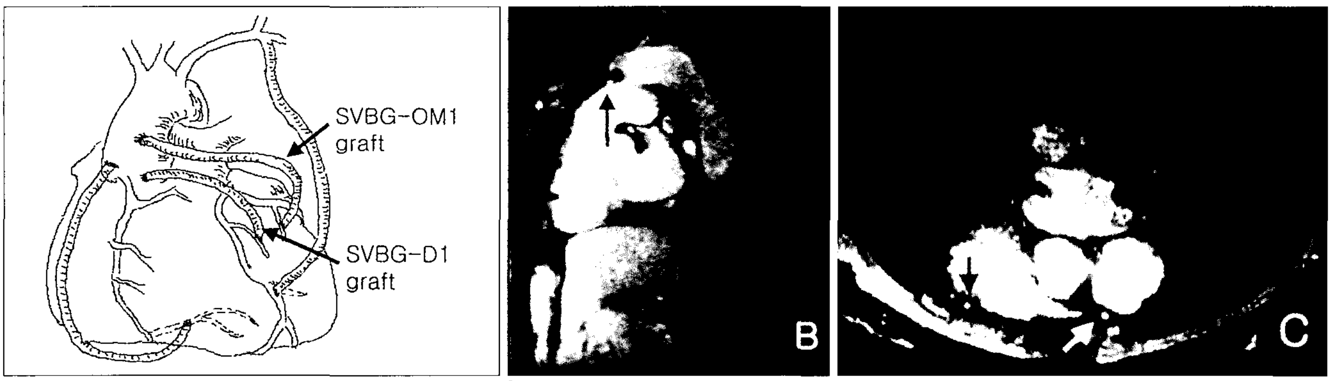


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Fig. 3. Schematic presentation of the location and course of saphenous vein coronary bypass grafts (to PDA, LCx branches: OM1, obtuse marginal and D1, diagnonal) and left internal mammary artery coronary bypass graft (LAD) (**a**) Only SVBG-OM1 graft is seen in a sagittal plane, while a SVBG-D1 graft is invisible (**b**). SVBG-PDA graft (white arrow) and LIMA-LAD graft (black arrow) are shown (**c**).

right internal mammary artery (RIMA) and the adjacent vein were clearly apparent. This patient showed an angina, which might suggest a slow flow of the bypass grafts, indicating dysfunction.

6) Type 6: SVBG-PDA or -RCA graft

The SVBG-PDA graft was seen in three consecutive slices and patent LAD was apparent very clearly as indicated in Figure 8, a-b. In this case intact LIMA and RIMA were visible as well.

Discussion

It has been difficult to observe LIMA-LAD grafts using MR imaging because metallic artifacts of the sternum obscured the grafts near the sternum. Recently people have reported successful visualization of LIMA graft using contrast agent enhancement. LIMA grafts were not seen mostly in the superior transverse plane of heart, but it was possible to observe it in the more inferior plane close to the position of anatomosis to LAD, where it presented bright spot due to patent flow inside LAD. There were three invisible LIMA-LAD grafts even in the inferior planes, suggesting the presence of stenotic pathologies. This observation may indicate that invisibility of the LIMA graft may be depended on the position of obstruction of main coronary artery and anatomosis position of the graft.

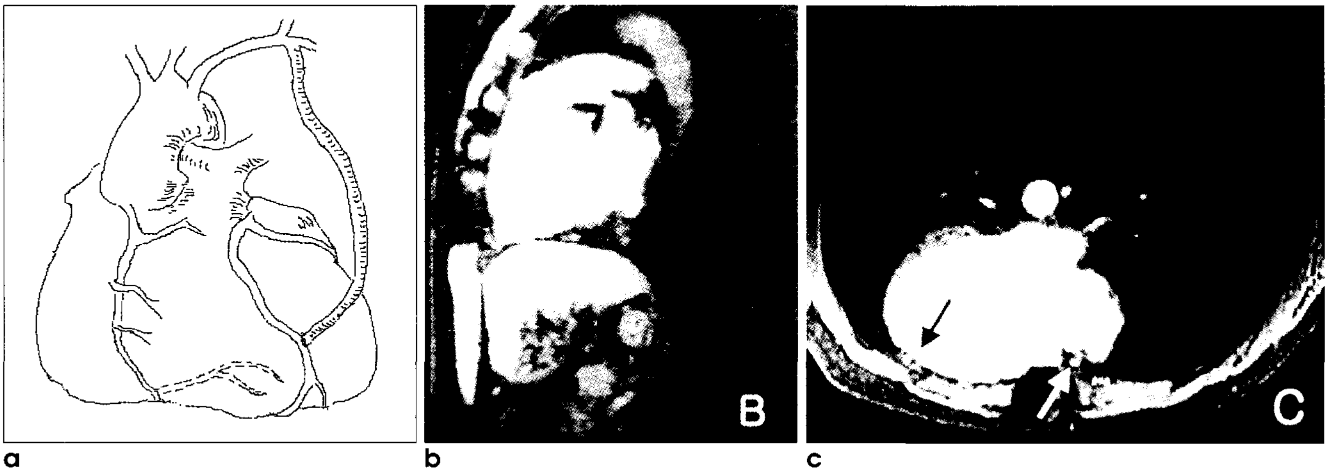

Fig. 4. Schematic presentation of only LIMA-LAD graft in type 2 configuration (**a**). Therefore no graft is shown in a sagittal plane as expected (**b**), while LIMA-LAD graft (black arrow) and intact RCA (white arrow) are visible at the level of four chamber in a transverse plane (**c**).

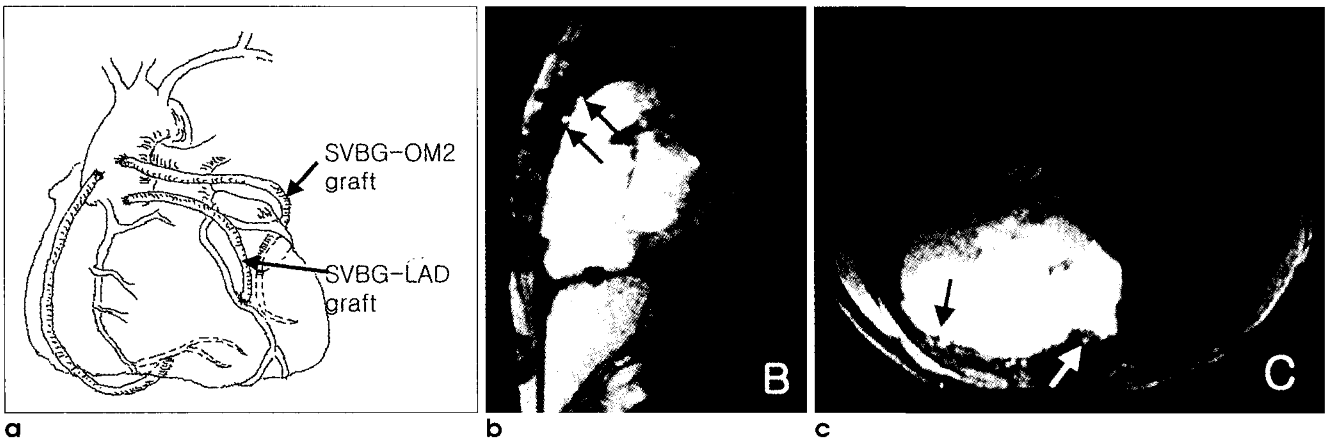

Fig. 5. Schematic presentation of SVBG-LAD and SVBG-OM2 (LCx branch) grafts, which could be shown in a sagittal plane and of SVBG-PDA graft (type 3) (**a**). SVBG-LAD graft (lower white arrow) and SVBG-OM2 graft (upper white arrow) are seen clearly in a sagittal plane (**b**). SVBG-PDA graft (white arrow) and intact LAD (black arrow) are seen at the level of four chamber in a transverse plane (**c**).

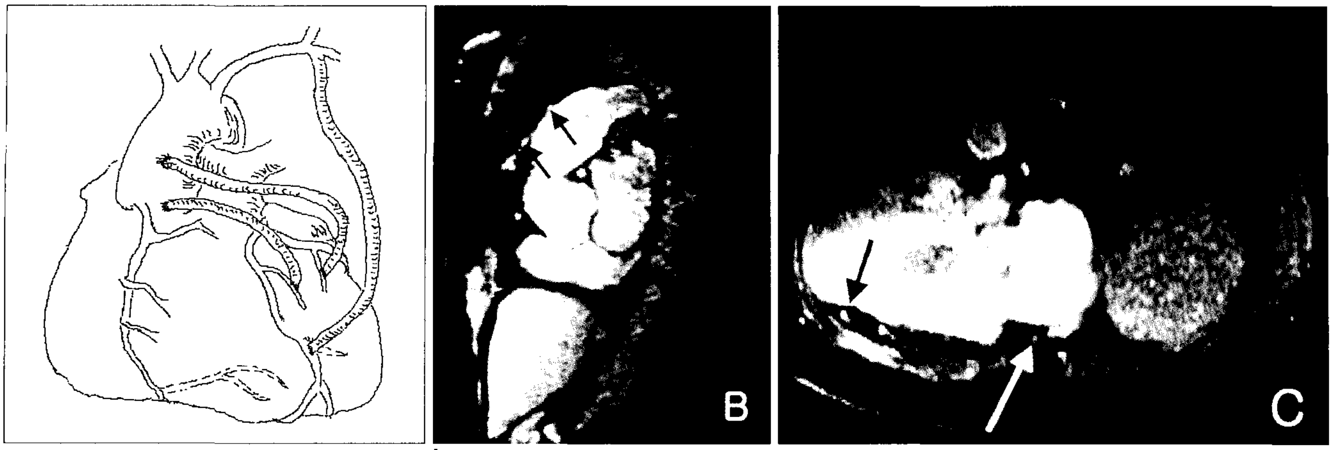

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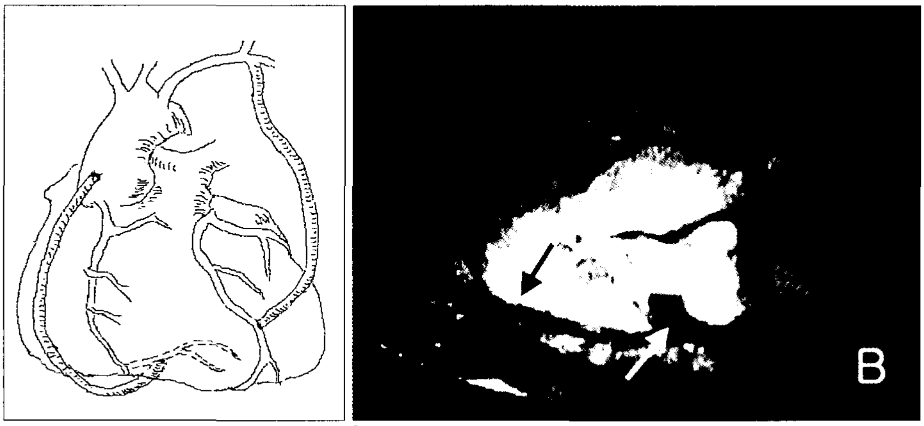
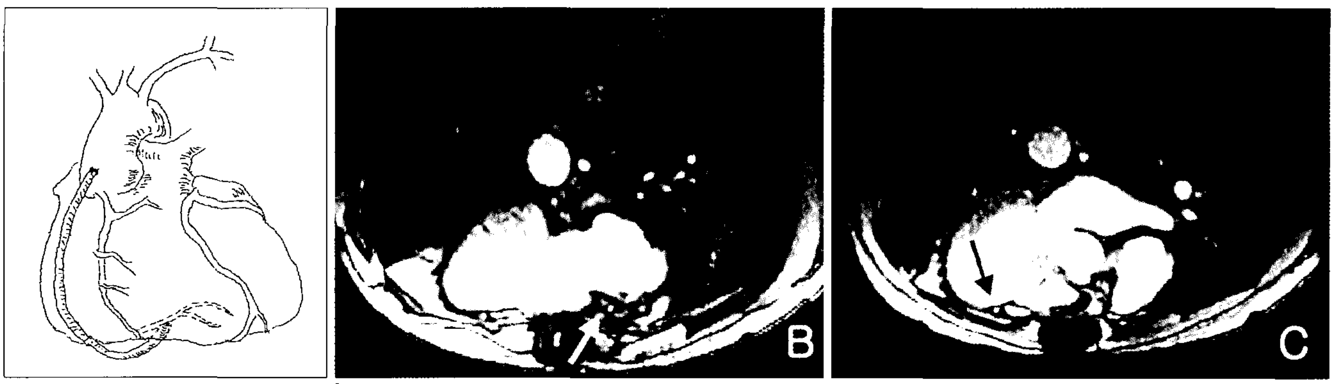
Fig. 6. Schematic presentation of SVBG-OM1 and SVBG-D1 grafts, which could be shown in a sagittal plane and of LIMA-LAD graft (type 4) (**a**). SVBG-D1 graft (lower black arrow) and SVBG-OM1 graft (upper black arrow) are seen clearly in a sagittal plane (**b**). Intact RCA (white arrow) and LIMA-LAD graft (black arrow) are seen at the level of four chamber in a transverse plane (**c**).



a b

Fig. 7. Schematic presentation of a LIMA-LAD graft and a SVBG-PDA graft (type 5) (**a**). SVBG-PDA graft (right arrow) and LIMA-LAD graft (left arrow) are not seen clearly at the level of four chamber in a transverse plane, which is an abnormal finding in this symptomatic patient (**b**).



a b c

Fig. 8. Schematic presentation of only SVBG-PDA graft (type 6) (**a**). SVBG-PDA graft (white arrow, **b**) and intact LAD (black arrow, **c**) are seen clearly in a transverse plane, respectively.

In case RCA was not accessible due to severe calcification the bypass graft was anatomosed to PDA. A graft to PDA may be more curved due to the surface of heart than a graft to main RCA, which may make the imaging slice align not perpendicular closely by chance to the flow direction inside the grafts to PDA. These possibilities may invoke low sensitivity of imaging of the flow inside the SVBG-PDA grafts. Imaging slice perpendicular to the grafts is necessary to visualize the patency of the grafts with maximum sensitivity, which additionally depends on flow velocity inside the graft. Therefore it can be assumed that the graft was not seen clearly due to slow flow in the graft for some reason, such as stenosis or partial obstruction. However in case of complete invisible grafts a possibility of obstruction inside the grafts would be increasing compared to the mismatched orthogonality between the selected imaging slice and grafts flow.

Determining patency of grafts does not exclude the presence of CABG stenosis, nor does it obviate the need for catheterization in a patient with postoperative angina. However, establishing patency of a CABG in the early postoperative period in symptomatic patient is of great clinical value because occlusion is likely due to acute thrombosis rather than to chronic atherosclerotic narrowing. Therefore, a noninvasive test to directly visualize grafts is important and would provide more specific information than indirect tests that evaluate for myocardial perfusion and wall motion abnormalities.

Conclusion

It was possible to evaluate the patency of CABG using breath-hold segmented K-space 2D-FASTCARD technique. Imaging perpendicular to CABG was important to visualize the flow inside a CABG with maximum sensitivity. Internal mammary artery grafts were easily visible particularly in the transverse plane proximal to the anastomosis to the LAD or its branch. However, any invisible bypass grafts should be further studied with different imaging planes or by conventional angiography for confirmation of abnormalities.

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대한자기공명의과학회지 7:22-30(2003)

호흡멈춤상태에서 K-space분할 CINE 자기공명영상기법을 이용한 관상동맥우회로의 혈류개방성의 검사

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목적: 본 연구에서는 호흡멈춤 K-space 분할 2D-FASTCARD 자기공명영상 기법에 의한 관상동맥우회로내의 혈류 개방성 검사의 임상적 유용성을 조사하였다.

대상 및 방법: 관상동맥우회로 시술을 한 38명의 환자에서 내유동맥의 수는 36개이었고 대복제정맥편은 56개였다. 2차원 FASTCARD 기법을 이용하여 sagittal 과 transverse평면에서 13-18초 동안 호흡을 멈추고 영상을 심장박동주기에 맞추어 획득하였다. 신호크기-영상의 hard copy를 이용하여 관상동맥우회로가 예상되는 지점에서 혈류에 의한 작은 원형부분이 밝게 보이면 해당 graft가 개방되었다고 판독하였다.

결과: 시술 환자의 다양한 관상동맥우회술의 양상에 따라 분류하여 Sagittal평면과 transverse평면에서 내유동맥편과 대복제정맥편의 개방성을 검사하였다. 좌회선지관상동맥의 분지로 연결되는 대복제정맥편은 Sagittal평면에서, 좌전하행지 관상동맥 혹은 그의 분지나 우관상동맥으로 연결되는 내유동맥편 혹은 대복제정맥편은 transverse평면에서 최대 감도의 개방성 영상을 보였다. 전체 38명의 환자 중에 23명의 영상획득 가능환자에서 45개의 관상동맥우회로가 보였으며 9개가 보이지 않았다. 증상이 있던 두 명의 환자중 2개의 관상 동맥우회로가 보이지 않았다.

결론: 호흡멈춤 K-space 분할 2D-FASTCARD 자기공명영상 기법으로 관상동맥우회로의 혈류 개방성의 비침습적 평가가 가능하다. 그러나 이 방법으로 보이지 않는 관상동맥우회로는 조영제를 사용한 자기공명 혈관조영술이나 일반 혈관조영술등의 방법으로 그 진위를 재검사하여 확진하는 것이 필요하다.

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