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Feasibility and diagnostic accuracy of 16-slice multidetector computed tomography coronary angiography in 500 consecutive patients: critical role of heart rate

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Abstract
Purpose To evaluate the feasibility and diagnostic accuracy of multidetector computed tomography coronary (MDCT) angiography applied to an unselected heart-disease population, to identify all causes of unfeasibility of exams, the distribution of artifacts in every coronary segment and their influence on diagnostic accuracy of examination.
Materials and methods We evaluated 500 patients with different indications for invasive coronary angiography. All underwent coronary MDCT and ICA. 215 patients were pre-treated with metoprolol intravenously. In the whole population we studied native coronary arteries and in 141 cases the patency of coronary artery bypass grafts (CABG). The quality of MDCT images was graded as good, sufficient and insufficient.
Results We were able to evaluate the patency of all grafts, with the exception of 4 cases. Diagnostic accuracy of CABG evaluation was very high (sensitivity 100%, specificity 98.4%). In native coronary arteries the overall feasibility was 97.9%. The middle left circumflex artery, right coronary artery and posterior descending artery were the segments most often poorly visualized. The first cause of artifacts was misalignment related to high heart rate, followed by premature heart beats and calcified plaque. The population was separated into 3 groups: group 1: heart rate <55 bpm, group 2: 55–65 bpm, group 3: >65 bpm. In group 1, misalignment was significantly lower than in groups 2 and 3. On a segment-based analysis, overall feasibility was therefore significantly higher in group 1 vs group 2 and vs group 3. Images of good quality were significantly higher in group 1 (95.4%) than in group 2 (87%) and group 3 (71.8%). The higher image quality in group 1 impacts on the overall diagnostic accuracy of the exam. Indeed overall sensitivity is significantly higher in group 1 (89.5%) than in group 2 (86%) and group 3 (82.8%) and overall specificity is significantly higher in group 1 than in group 3.
Conclusions Multidetector computed tomography has a high feasibility and diagnostic accuracy for the evaluation of coronary artery disease in an unselected population. Good patient preparation (optimized beta-blocker therapy, correct breathing instructions) is essential for evaluating native coronary arteries while preparation with a beta-blocker is less relevant in bypass graft patients.

Keywords Beta-blocker therapy · Heart rate · Misalignment of slices

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Abbreviations

AHA	American heart association
CAD	Coronary artery disease
D1	First diagonal branch
D2	Second diagonal branch
ICA	Invasive coronary angiography
IMA	Internal mammary artery
LAD	Left anterior descending artery
LCX	Left circumflex artery
LMA	Left main artery
M1	First marginal branch
M2	Second marginal branch
MDCT	Multidetector computed tomography
MPR	Multiplanar reconstruction
NPV	Negative predictive value
PD	Posterior descending artery
PPV	Positive predictive value
RCA	Right coronary artery
VA	Vessel analysis
VR	Volume rendering

Introduction

Conventional invasive coronary angiography is currently the standard diagnostic method for the clinical evaluation of known or suspected coronary artery disease (CAD). The risk of adverse events is small, but serious and potentially life-threatening sequelae may occur, including arrhythmia, stroke, coronary artery dissection and access site bleeding (total complication rate 1.8%, mortality rate 0.1%) [1, 2]. Furthermore, catheterization induces some discomfort and mandates routine follow-up care. Therefore conventional invasive diagnostic angiography should be restricted to stringent clinical indications [1]. This situation constitutes the basis of the demand for a reliable noninvasive test. Studies with early versions of multidetector computed tomography (MDCT) scanners equipped with 4 detectors and a temporal resolution of 250 to 330 ms demonstrated the ability of cardiac CT to detect significant coronary stenosis in selected patients with high-image-quality data sets. However the clinical applicability of these methods was limited by the fact that almost one third of all coronary artery segments could not be evaluated owing to stair-step and motion artifacts and the presence of calcification, providing only low levels of diagnostic accuracy (sensitivity 63%, specificity 71%) [3]. The new generation of MDCT scanners permits simultaneous acquisition of image data in 16 parallel cross-sections with an in-plane resolution of 0.625 mm and a gantry rotation time of 400 ms. Many studies with 16-row devices have demonstrated improved diagnostic accuracy for the detection of significant stenosis in assessable coronary segments (sensitivity 92–95%, specificity 86–95%), with high global feasibility (88–100%) [4–11]. These reports are based on a relatively low number of patients (33 to 125) and on selected populations (patients with a positive stress test, suspected CAD, stable angina pectoris, known CAD). In this study we have evaluated the feasibility of MDCT applied to a large unselected heart-disease population including consecutive patients. Moreover, previous studies considered massive calcification and high heart rate (more than 65 bpm) as negative predictive factors for assessability of the exam [12–18], though in our experience the cut-off at 65 bpm seems to be too high and several other factors influence the feasibility of exams.

Finally the literature does not report precisely the incidence of all different causes of unfeasibility, with a segment-by-segment analysis.

The aim of our study was to identify all causes of unfeasibility of exams, to study the distribution of artifacts in every coronary segment and to show if a lower heart rate, obtained using beta-blocker therapy, could prevent the presence of most artifacts and improve the diagnostic accuracy of the examination.

Materials and methods

Study population

The study enrolment period was 2 years (from January 2004 to December 2005), during which we evaluated five hundred consecutive patients (333 male, mean age 65 ± 10 years) with different

indications for invasive coronary angiography (known CAD 238 cases, chest pain 93 cases, chest pain and cardiovascular risk factors 51 cases, dilated cardiomyopathy 41 cases, positive stress test 21 cases, aortic aneurysm 19 cases, heart valve disease 15 cases, arrhythmias 10 cases, hypertension 2 cases, other causes 10 cases), admitted to our hospital. All underwent coronary MDCT and invasive coronary angiography. In all cases we studied native coronary arteries and in 141 cases the patency of bypass grafts: 125 left-internal mammary artery (IMA) grafts, 13 right-IMA, 9 radial artery, 2 gastro-epiploic artery (GEA), and 153 saphenous vein grafts. Informed consent was obtained from all patients.

Patient preparation

Each patient with heart rate ≥65 beats/min was treated with single or multiple intravenous doses of metoprolol about 15 minute before the scan (215 patients = 43%, average dose 6.3 ± 1.5 mg).

Selective coronary angiography

Selective ICA was performed with a standard technique through a transfemoral approach. The coronary arteries were divided into segments following the American Heart Association classification also used for MDCT [19]: left main artery (LMA), proximal, middle and distal segments of the left anterior descending artery (LAD), first and second diagonal branches (D1 and D2), proximal, middle and distal segments of left circumflex artery (LCX), first and second marginal branches (M1 and M2), proximal, middle and distal segments of right coronary artery (RCA) and posterior descending artery (PD). The angiograms were assessed with quantitative coronary angiography software (QCA CAAS, Pie Medical, Maastricht, Netherlands) by three independent interventional cardiologists blinded to MDCT data. The severity of coronary stenoses was quantified on two orthogonal views, and a stenosis was classified as significant if the mean lumen diameter reduction was ≥50%.

MDCT scan protocol and image reconstruction

MDCT data were acquired using 16-slice CT (GE Medical Systems Light Speed Pro, USA) with 16 × 0.625 mm or 16 × 1.25 mm collimation and a gantry rotation time of 400 ms. According to the ''ECG-pulsing technique'' the tube current was modulated with a maximum current of 600 mA during a period between 40% and 80% of the R-wave to R-wave interval and a reduction by 80% during the remaining cardiac cycle. A tube voltage of 120 to 140 kV was applied according to the patient's body weight.

During the scan, a variable dose of Iomeprolo (Iomeron 400 mg/ml Bracco, Italy, average dose 110 ml ± 11 ml) was injected intravenously at a rate of 4.5 ml/s. To reduce the contrast agent volume [20] and hyper-attenuation in the superior vena cava and right heart [21] a saline solution (30 ml at 2.0 ml/s) was injected immediately after the contrast agent bolus. MDCT scan was acquired by the fluoroscopic bolus tracking technique during breath-hold (about 20 s), and evaluated by two independent expert readers with multiple approaches including volume rendering (VR), multiplanar reconstruction (MPR) and vessel analysis (VA) (CardioQ3 package, GE Medical Systems, USA). On the basis of the ''segment or burst reconstruction'' algorithm, the temporal resolutions were between 100 ms and 200 ms, depending on the heart rate.

MDCT image evaluation

The coronary arteries were classified according to the 15-segment model of the American Heart Association [19].

Segments with diameter ≤ 1.5 mm were excluded from the analysis, while segments in which the poor image quality did not allow evaluation of patency were classified as not assessable by two independent and blinded observers. Disagreements (258 out of 5385 segments, 4.8%) were resolved by consensus. Moreover in patients with CABG proximal segments were excluded from the analysis, while all segments distal to the anastomosis were included.

The quality of images, judged on the basis of the absence of artifacts and on the possibility of correctly evaluating the vessel canalization (patency, presence of stenosis, occlusion) on the reconstructed image was graded as: good (absence of artifacts, possibility of correctly evaluating the vessel canalization), sufficient (presence of mild artifacts, possibility of evaluating the vessel canalization), insufficient (presence of large artifacts, no possibility of evaluating the vessel canalization, cause of unfeasibility).

The causes of impaired image quality (unfeasibility) were classified as presence of calcified plaque, motion artifacts related to non-respect of breath-hold or chest movement, misalignment of slices related to changes in heart rate or high heart rate during the scan, premature ventricular beats, presence of cardioverter/pace-maker leads, cardiac venous system, intramyocardial tract, image noise/suboptimal contrast enhancement, presence of coronary stent. In detail, the artifact due to calcified plaque was defined as large high-density lesion, extending along the wall, causing partial volume and beam hardening artifact; misalignment was defined as impairment of image quality caused by derangement of different vessel portions, resulting in out-of-phase vessel contours; interferences due to cardioverter/pace-maker leads were generally star artifacts covering the coronary tree; the cardiac venous system may interfere with the imaging of a specific coronary segment mainly when it is dilated and, despite technical artifices, the adjacent coronary segment is not entirely visualized. Figure 1 shows some examples of these artifacts.

Statistical analysis

The global feasibility of the MDCT scan was measured. MDCT accuracy (sensitivity, specificity, positive predictive value and negative predictive value) was estimated on a segment-based model and on a patient-based model (these diagnostic parameters are expressed with a 95% confidence interval). Segment-based analysis included all evaluable segments and nonevaluable segments that were censored as ''positive'' [22]. On a patient based-analysis, patients with at least 1 detected stenosis >50% in a CABG or a native post-anastomotic coronary arteries were classified as ''positive''. Differences in feasibility and accuracy between the 3 groups in the presence of different artifacts were calculated by the Chi-Squared analysis. Parameters were expressed with a 95% confidence interval. The correlation between misalignment and heart rate was measured by analysis of maximum likelihood estimates (with 95% confidence interval).

Results

Mean heart rate after intravenous metoprolol was 61.5 ± 9.1 bpm. All patients underwent a complete MDCT scan without complications. On the basis of exclusion criteria 775 segments were excluded due to a diameter <1.5 mm and 1340 segments were excluded in patients with CABG (proximal segments). Therefore 5385 out of 7500 segments were analyzed in the entire population. The overall feasibility of MDCT was 97.96% (5275 out of 5385 segments).

Segment-based analysis

Table 1 reports feasibility in the 15 different segments of the coronary arteries. Excellent results were obtained for the LM and LAD. A lower feasibility characterized the middle LCX (percentage of non-assessable segments: 4.1%), the PD artery (3.06%) and all 3 segments of the RCA (proximal 2.78%, middle 6.12%, distal: 4.1%). We found 110 segments not assessable (2.04%) and we analyzed the different causes of unfeasibility, reported in Table 2. The first cause of unfeasibility (corresponding to a large artifact) was the misalignment of slices related to variation of heart rate or high heart rate (42 artifacts), followed by misalignment of slices related to premature ventricular beats (16 artifacts), and presence of massive calcified plaque (13 artifacts). In our population we found a very strong correlation between heart rate and misalignment of slices with an estimated value of 1.101, determining the probability of an increase in misalignment of almost 10% for each 1 bpm increase in heart rate. To better investigate the role of heart rate in determining artifacts we decided to separate the

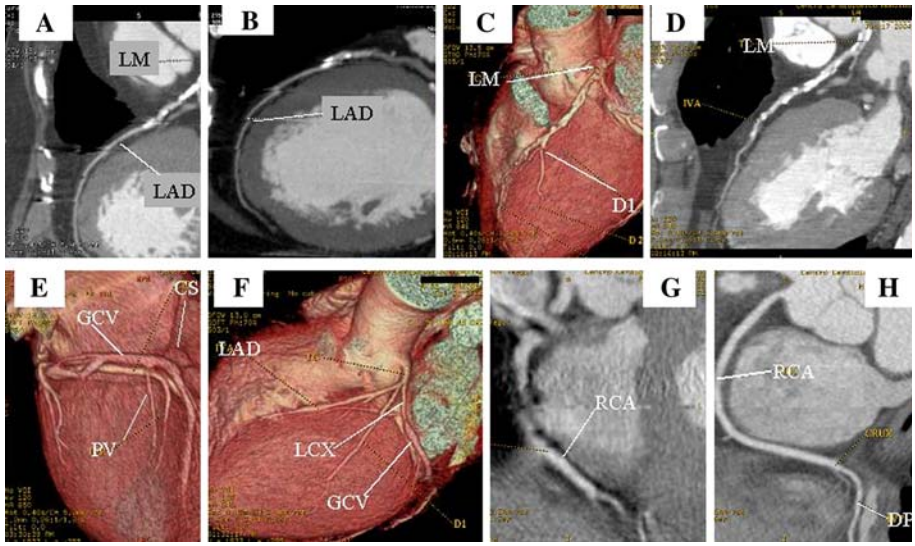

Fig. 1 Examples of different causes of artifacts. (**A** and **B**). Multiplanar reconstruction (MPR) of left anterior descending artery: misalignment related to variable heart rate or premature beat; (**C** and **D**). Volume rendering (VR) reconstruction (**C**) and MPR of left anterior descending artery: massive calcification on LM and LAD; (**E** and **F**). VR reconstruction of coronary tree: great cardiac vein and its branches hide proximal (**E**) and middle-distal segment (**F**) of left circumflex artery (LCX); (**G**) and H. MPR of right coronary artery (RCA): artifact on the middle segment of RCA related to excessive contrast medium in right atrium (**G**); a correct visualization of RCA with double-injector protocol (**H**). LM: left main artery; LAD: left anterior descending artery; D1: first diagonal branch; LCX: left circumflex artery; RCA: right coronary; PD: posterior descending artery; CS: coronary sinus; GCV: great cardiac vein; PV: posterior vein

Table 1 Percentage of unfeasibility (insufficient image quality) of different segments of coronary arteries in the three study groups

	Overall	Group 1	Group 2	Group 3
LM	0.55%	0%	0%	1.92%
LAD proximal	0.83%	0%	0%	2.88%
LAD middle	1.94%	0%	2.51%	1.92%
LAD distal	2.22%	1.04%	1.88%	3.85%
D 1	0.83%	1.04%	0.62%	0.96%
D 2	0.27%	0%	0.62%	0%
LCX proximal	2.22%	1.04% *	0.62% β	6.73%
LCX middle	4.10%	3.12%	3.14%	7.69%
LCX distal	0%	0%	0%	0%
M 1	1.11%	0%	0.62%	3.85%
M 2	0.27%	0%	0%	0.96%
RCA proximal	2.78%	3.12%	1.88%	4.81%
RCA middle	6.12%	1.04%ϕ *	7.54%	7.69%
RCA distal	4.10%	1.04% *	4.40%	6.73%
PD	3.06%	0%	3.77%	2.88%
Total	2.04%	0.76% ω α	1.84%β	3.53%

ϕ $P < 0.05$ vs group 2; * $P < 0.05$ vs group 3; ω $P < 0.01$ vs group 2

α $P < 0.001$ vs group 3; β $P < 0.05$ vs group 3

whole population into 3 groups: group 1 (134 patients): heart rate <55 bpm, group 2 (222 patients): heart rate 55 to 65 bpm, group 3 (144 patients): heart rate >65 bpm. Table 3 shows the distribution of artifacts (causes of unfeasibility) in the 3 groups. We noted that, in group 1,

Table 2 Causes of unfeasibility in the different segments of the coronary tree

Breath	PHB	CA	H.R.	ICD	V.S.	I.M.	MdC	Stent	TOTAL
LM		1		1					2
LAD	4	6	3	5		1	3		22
LCX	2	3	4	10	1	8			28
RCA	4	6	6	26	5	1	2	6	2	58
Total	10	16	13	42	6	10	5	6	2	110

Breath = motion artifacts due to breath/chest movement, PHB = premature heart beats, CA = calcium, H.R. = misalignment due to heart-rate variation/high heart rate, ICD = cardioverter/pace-maker, V.S. = cardiac venous system, I.M. = intramyocardial tract, MdC = contrast medium enhancement. LAD including artifacts of all segments of LAD, D1 and D2. LCX including artifacts of all segments of LCX, M1 and M2. RCA including artifacts of all segments of RCA and PD

Table 3 Causes of unfeasibility in the different segments of the coronary tree in the 3 groups

	Breath	PHB	CA	H.R.	ICD	V.S.	I.M.	MdC	Stent	TOTAL
GROUP 1										
LAD	1						1			2
LCX	1		3							4
RCA			2	2				1		5
Total	2	0*	5	2$\alpha\omega$	0	0$\beta\psi$	1	1	0	11
GROUP 2										
LAD		5	1	2			1			9
LCX	2			3		2				7
RCA	3	1	3	9	4	1	2	3	2	28
Total	5	6	4	14$\otimes\omega$	4	3$\blacklozenge\psi$	3	3	2	44
GROUP 3										
LM		1		1						2
LAD	2	1	2	3		1	1			10
LCX	1	3	1	8	1	6				20
RCA		5	1	14	1			2		23
Total	3	10*	4	26$\alpha\otimes$	2	7$\beta\blacklozenge$	1	2	0	55

* $P < 0.01$ group 1 vs group 3; α $P < 0.001$ group 1 vs group 3; β $P < 0.025$ group 1 vs group 3 ω $P < 0.05$ group 1 vs group 2; ψ $P < 0.001$ group 1 vs group 2; $\otimes$ $P < 0.01$ group 2 vs group 3 $\blacklozenge$ $P < 0.05$ group 2 vs group 3

Same abbreviations as in Table 2

unfeasibility due to misalignment was significantly lower than in groups 2 and 3, showing that misalignment is notably reduced with very low heart rate. The difference between groups 2 and 3 was also significant. Others causes of unfeasibility (premature beats and artifacts due to the venous system) were significantly lower in group 1 vs group 3 and the presence of artifacts related to venous system interference was also significantly lower in group 1 vs group 2 and in group 2 vs 3.

This heart-rate related reduction of artifacts in group 2 and even more in group 1 (reduction in misalignment directly related to heart rate, reduction in premature beat related to action of beta-blocker, and in artifacts due to the venous system that, at very low heart rate, is easier to distinguish from the coronary artery tree) impacts on the overall feasibility of the exam (table 1). MDCT unfeasibility is significantly lower in group 1 vs group 2 (0.76% vs 1.84%) and vs group 3 (0.76% vs 3.53%). Unfeasibility is also significantly lower in group 2 vs group 3 (1.84% vs 3.53%). In comparison with other groups, the higher feasibility and the reduction of artifacts (misalignment due to high heart rate and premature beat and artifacts related to venous system interference) in group 1 is mainly due to the significant improvement in the evaluation of segments having poor feasibility in the overall population, such as the middle and distal RCA, where misalignment is

the major artifact factor, and the proximal LCX whose major artifact factors are misalignment, venous system and premature beats. The difference in feasibility of assessment of the proximal LCX between groups 2 and 3 is also significant.

Table 4 shows the image quality evaluation in the three groups. Images of good quality were significantly higher in group 1 (95.4%) than in group 2 (87%) and group 3 (71.79%). Just like images of insufficient quality (unfeasible evaluation), images of sufficient quality were significantly less frequent in group 1 than in group 2 and group 3.

Table 5 shows the diagnostic accuracy in the 3 groups of patients including segments for analysis only (n = 5275, one-hundred ten segments judged as not assessable (insufficient quality of image due to presence of large artifacts) were excluded from this analysis of diagnostic accuracy). In group 1, overall sensitivity is significantly higher than in group 2 (89.5% vs 86%) and group 3 (89.5% vs 82.8%) due to a significantly higher sensitivity in all segment of the RCA than groups 2 and 3 and to a significantly higher sensitivity in the PD than group 3. In group 2, overall sensitivity is significantly higher than group 3 (86% vs 82.8%) due to a significantly higher sensitivity in all segment of the RCA. Also the overall specificity of group 1 is higher than group 2 (98.2% vs 96.3%) and significantly higher than group 3 (98.2% vs 95%), due to a significantly higher specificity in the proximal RCA vs group 3 and the middle RCA vs groups 2 and 3.

Overall positive predictive value (PPV) and negative predictive value (NPV) were respectively 86.3% and 96.2%. PPV and NPV were respectively 87.1% and 98.3% for group 1, 86.8% and 96.2% for group 2 and 85.1% and 95.1% for group 3. In group 1 NPV is significantly higher than in group 3 ($P < 0.05$).

Table 6 shows the diagnostic accuracy in the 3 groups of patients including all segments for analysis with nonevaluable segments censored as ''positive''(n = 5385). Results obtained including or excluding not assessable segments were very similar (Tables 5 and 6).

Table 7 shows the feasibility and diagnostic accuracy of evaluation of bypass graft patency in 141 patients. Feasibility of evaluation of bypass grafts was very high (98.65%). We judged only 4/302 cases not assessable and all four artifacts were due to surgical technique: 3 IMA grafts with particularly long and closely-spaced metallic clips and one saphenous vein graft because of anastomosis with a new generation magnetic device (Fig. 2). Also overall sensitivity, specificity, positive predictive value and negative predictive value were very high (100%, 98.4%, 96.3% and 100% respectively). MDCT correctly diagnosed all 35 grafts shown as occluded on invasive coronary angiography. All 45 significant stenoses of grafts detected by ICA were correctly diagnosed by MDCT, with three cases of mild disparity in terms of the severity of the lesion (slight overestimation on MDCT) observed in two segments of venous grafts (classified as false positives).

Patient-based analysis

On a patient based-model the overall feasibility, sensitivity, specificity, positive predictive value and negative predictive value were 92% (460/500 patients), 88.8%, 93.4%, 85.4% and 97.1% respectively. Feasibility was significantly higher in group 1 vs group 2 (96.3%, 129/134 patients vs 91.9%, 204/222 patients, $P < 0.01$) and vs group 3 (96.3% vs 88.2%, 127/144 patients, $P < 0.01$). Feasibility is also significantly higher

Table 4 MDCT image quality evaluation in the three groups of patients

	Group 1	Group 2	Group 3	Total
Good	1374 (95.4%)ψ	2077 (87%)$\otimes$	1120 (71.79%)	4571 (84.88%)
Sufficient	55 (3.81%)ψ	264 (11%)$\otimes$	385 (24.67%)	704 (13.07%)
Insufficient (unfeasibility)	11 (0.76%)$\omega\alpha$	44 (1.84%)β	55 (3.53%)	110 (2.04%)

ω $P < 0.01$ vs group 2; α $P < 0.001$ vs group 3; β $P < 0.05$ vs group 3; ψ $P < 0.001$ vs group 2 and 3; $\otimes$ $P < 0.001$ vs group 3

Table 5 MDCT diagnostic accuracy in the three groups of patients: segment-based analysis (segments for analysis only; $n = 5275$)

	Group 1 (Sens/spec)	Group 2 (Sens/spec)	Group 3 (Sens/spec)	Total (Sens/spec)
LM	77.1/95.6%	80.2/96.5%	79.2/97%	78.8/96.8%
LAD proximal	96.6/92.5%	94.8/90%	97/91.3%	96.7/91.4%
LAD middle	96.3/92%	95.9/92.2%	96.6/91%	96.4/91.9%
LAD distal	98.2/99.5%	97/97.6%	99/99.5%	98.2/99%
D 1	68.3/94.5%	72.4/91.4%	64.2/92.2	67.5/92.3%
D 2	98.5/96.3%	95.2/98.3%	98.2/98.8%	97/98%
LCX proximal	96.3/98.2%	99.2/98.5%	99.1/98.1%	99/98.3%
LCX middle	99.1/96.5%	95.8/93.4%	96.1/94.5%	98.6/94.4%
LCX distal	72.2/97.6%	74.1/99.3%	70.6/98.3%	71.4/98.2%
M 1	74.6/100%	74.8/100%	75.6/100%	75/100%
M 2	88.8/99.2%	88.1/97.3%	87.9/99.1%	88/99
RCA proximal	90.2ψ/96.3%⊗	84.2⊗/95.3%	71.2/91.1%	80/94.2%
RCA middle	95.2ψ/94.6%ψ	90.6⊗/89.2%⊗	77.1/83.2%	91.7/91.7%
RCA distal	80.2ψ/99.2%	76.6⊗/98.2%	65.2/97%	72.7/98.3%
PD	77.3⊗/100%	74.5/100%	72.2/100%	75/100%
Global	89.5ψ/98.2%⊗	86.0⊗/96.3%	82.8/95%	86.1/96.4%

ψ $P < 0.01$ vs group 2 and 3; ⊗ $P < 0.01$ vs group 3

Table 6 MDCT diagnostic accuracy in the three groups of patients: segment-based analysis (all segments for analysis with nonevaluable segments ''positive''; $n = 5385$)

	Group 1(Sens/spec)	Group 2 (Sens/spec)	Group 3 (Sens/spec)	Total (Sens/spec)
LM	80.1/92.6%	80/94.5%	79/93.2%	80.1/93.8%
LAD proximal	96.6/90.1%	96.1/88.1%	97.1/87.3%	96.8/88.9%
LAD middle	96.5/90%	96.7/90.2%	96.9/91%	96.6/90.4%
LAD distal	98.3/98.5%	97.1/96.5%	96/97.5%	97.1/97%
D 1	72.3/91.2%	73.5/90%	68.2/91.2	70.5/90.5%
D 2	98.6/96%	95.8/97.4%	98.2/96.2%	97.1/96.9%
LCX proximal	96.2/97.1%	99.3/98%	99.1/97.3%	99/98%
LCX middle	99.1/96.5%	95.8/93.4%	96.1/94.5%	98.6/94.4%
LCX distal	74/95.5%	74.5/96.2%	73.7/96.3%	74.1/96%
M 1	76.5/98.1%	75.8/99%	75.2/98.2%	75.4/98.7%
M 2	89.5/99.5%	88.5/98.1%	87.1/99%	88.2/98.4%
RCA proximal	91.1ψ/95.9%⊗	84.9⊗/94.2%	74.1/91%	83.1/94%
RCA middle	95.5ψ/91.5%⊗	90.9⊗/89.1%⊗	80.1/82.7%	90.1/90.2%
RCA distal	80.5ψ/97.2%	76.7⊗/96.8%	67.2/97%	73.7/96.9%
PD	78.3⊗/99.5%	74.9/100%	72.6/99.6%	75.4/99.8%
Global	90.8ψ/95.8%⊗	86.9⊗/94%	82.9/92.7%	87/94%

ψ $P < 0.01$ vs group 2 and 3; ⊗ $P < 0.01$ vs group 3

Table 7 MDCT feasibility and diagnostic accuracy of bypass graft imaging: segment-based analysis

Type of graft	Number of grafts	Number of artifacts	Type of artifact	Feasibility	Sens	Spec
Right-IMA	13	1	Metallic clip	92.31%	100%	100%
Left-IMA	125	2	Metallic clip	98.4%	100%	100%
Radial artery	9	0		100%	100%	100%
GEA	2	0		100%	100%	100%
Vein graft	153	1	Magnetic clip	99.35%	100%	97.1%
Total	302	4		98.68%	100%	98.4%

IMA = internal mammary artery; GEA = gastro-epiploic artery

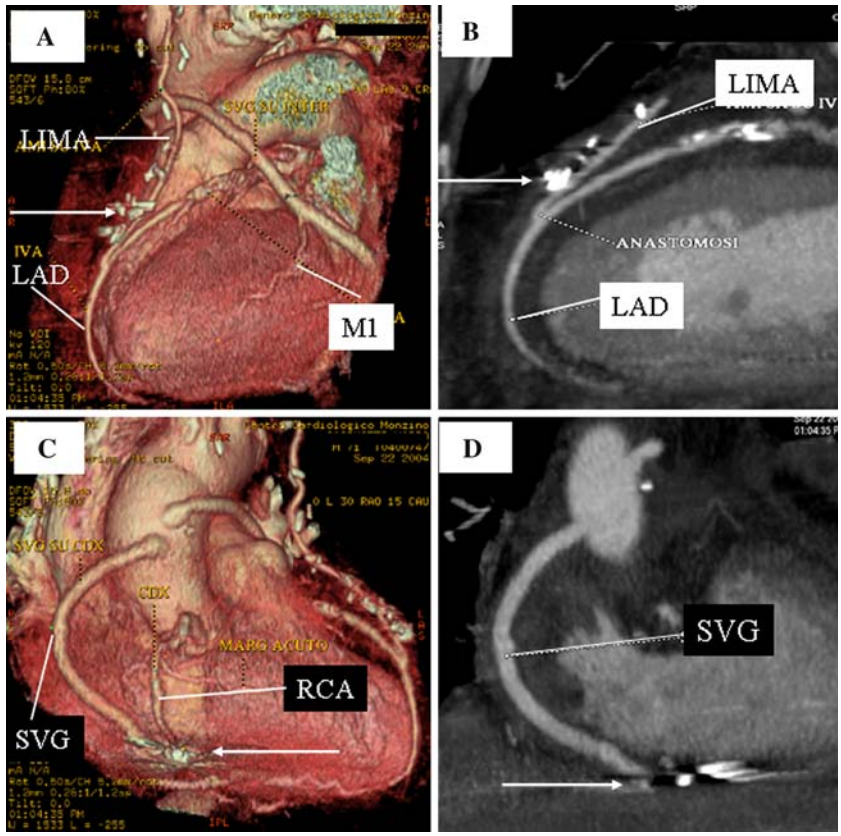

Fig. 2 (**A** and **B**). Volume rendering (VR) reconstruction (**A**) and multiplanar reconstruction (MPR, **B**) of left internal mammary artery (LIMA) anastomized on middle segment of left anterior descending artery (LAD): three closely-spaced metallic clips on distal portion of LIMA (arrow). (**C** and **D**). Volume rendering (VR) reconstruction (**C**) and multiplanar reconstruction (MPR, **D**) of saphenous vein graft anastomized on the distal right coronary artery (RCA) with magnetic device (arrows). LIMA: left internal mammary artery; SVG: saphenous vein graft; LAD: left anterior descending artery; M1: first marginal branch; LCX: left circumflex artery; RCA: right coronary artery; PD: posterior descending artery

in group 2 vs group 3 (91.9% vs 88.8%, $P < 0.01$). Sensitivity was significantly higher in group 1 vs group 2 (94.1% vs 88.7%, $P < 0.01$) and vs group 3 (94.1% vs 82.1%, $P < 0.01$). Sensitivity is also significantly higher in group 2 vs group 3 (88.7% vs 82.1%, $P < 0.01$). Specificity was significantly higher in group 1 vs group 3 (95.7% vs 91.4%, $P < 0.01$). No significant difference between group 1 and group 2 (95.7% vs 93.3%).

PPV and NPV were respectively 86.5% and 98.6% for group 1, 85.3% and 96.9% for group 2 and 85.1% and 95.5% for group 3. In group 1 NPV is significantly higher than in group 3 ($P < 0.05$).

Discussion

A main finding in this study is that overall feasibility in the evaluation of native coronary arteries in an unselected population is high (98%) and that heart rate control can significantly reduce the artifacts related to misalignment. Even though the large majority of cases (455 patients) and segments were imaged by the technique without substantial artifacts, we could not evaluate 110 coronary segments distributed in 45 patients. In this study we examined in detail the causes and location of artifacts. Coronary portions with most artifacts were the proximal RCA, middle RCA, distal RCA, proximal LCX, middle

LCX and PD. High heart rate and massive coronary calcification are known to be major causes of unfeasibility of MDCT coronary angiography [12–18]. We found that the conventional heart-rate cut-off suggested by previous studies (heart rate ≥65 bpm), is too high and that performing the exam with a lower heart rate (<55 bpm) can further improve the quality of images, feasibility and possibly diagnostic accuracy. The role of heart rate in MDCT feasibility is even more important because beta-blocker therapy [23] not only modulates heart rate, but may also reduce premature ventricular beats [24, 25], which represent the second cause of artifacts. Analyzing causes of artifacts, we found in descending order: misalignments related to variable/high heart rate (42 artifacts), premature beats (16 artifacts), calcified plaque (13 artifacts), cardiac venous system (10 artifacts) and motion artifacts (related to incomplete breath-hold or chest movement) (10 artifacts).

Four of the nine causes of artifacts were classifiable as modifiable: misalignment due to variable/high heart rate, premature beats (potentially reduced by beta-blocker therapy), image noise/suboptimal contrast enhancement that can be corrected using a double-bolus injection protocol, and motion artifacts, avoidable by explaining to patients the importance of breath-hold and immobility during scanning. Four other causes of artifacts were classified as not modifiable: presence of cardioverter/pace-maker leads, presence of coronary stent, intramyocardial coronary tract and massive calcified plaque. Another cause, a hypertrophic cardiac venous system, apparently non-modifiable, appeared to be modifiable in our study; in fact, at very low heart rate, it is possible to separate better these structures of similar density (cardiac arterial and venous systems) and obtain better image quality. Therefore four of the five major causes of artifacts were potentially modifiable (high heart rate, premature beats, venous system and breath-hold or chest movement). Of these, two are related to heart rate decrease (high heart rate and premature beats), but the venous system too benefits from a decrease in heart rate. The fact that perfect control of heart rate is very important is supported by a high correlation between misalignment and heart rate (estimated value = 1.1): an increase of 1 bpm is sufficient to increase the probability of misalignment by 10%. Misalignment is the major cause of artifacts in 4 out of 5 segments with poor feasibility: the proximal RCA, middle RCA, distal RCA, PD and it is the second cause also in the middle LCX. Therefore misalignment related to high heart rate is located mostly on the RCA segments (50% of total misalignment). The importance of heart-rate control on the reduction of artifacts due to misalignment and of artifacts due to venous system interference is well demonstrated in group 1, in which misalignments due to high heart rate are significantly lower than in group 2 and group 3. This impacts on the overall feasibility of the exam, which is better in group 1 than in group 2 and, still more clearly, group 3. The importance of heart-rate control on the reduction of artifacts due to misalignment is also confirmed by the influence of heart rate on image quality. Images of good quality were significantly more frequent in group 1 than in group 2 and group 3. and images of sufficient quality were significantly fewer in group 1 than in group 2 and group 3. Sub-optimal image quality (classified as sufficient) is chiefly due to the presence of misalignment related to variable heart rate that influences the correct evaluation of vessel canalization mainly in the RCA and PD. The higher image quality impacts on the overall diagnostic accuracy of the exam. Indeed overall sensitivity is significantly higher in group 1, due to a significantly higher sensitivity in segments in which the artifacts due to misalignment are more frequent. Incorrect breath-hold or chest motion and massive calcified plaque obviously do not show correlation with heart rate and are similar in the 3 groups. Whereas for massive calcification it is difficult to foresee technological improvements overcoming the problem, artifacts related to motions may be significantly reduced when scanners able to acquire up to 64 slices (allowing a marked reduction in time of acquisition) become generally available. These improvements in temporal resolution will probably reduce dependence on heart rate. We can also expect a significant reduction in misalignment at higher heart rates and a lower probability of artifacts related to premature beats because of the short time (5–6 s) for acquisition required by the new 64-slice

scanners. Moreover the recently introduced dual-source technology, thanks to high and heart rate independent temporal resolution, permits imaging of the coronary arteries without motion artifacts in a increased number of patients as compared to earlier scanner generations [26].

Bypass grafts (venous and arterial conduits) are ideal vessels for evaluation by MDCT because of their greater diameter vs native coronary arteries, their direction with reference to the plane of the cross beam, their spatial fixation (thanks to relative independence from heart contraction) and the uncommon presence of severely calcified lesions [27]. Because of these favorable characteristics, conventional computed tomography has been used for noninvasive assessment of venous conduits after CABG since the early 1980s [28] and the first-generation 4-slice MDCT devices showed high diagnostic accuracy in the detection of venous and arterial occlusions. Further improvement in diagnostic accuracy has been shown with 16 slices scanners. The feasibility of complete evaluation of bypass graft patency in our population is very high (98.6%). These very good results are mainly due to the fact that the misalignment due to high heart rate, has little influence on the quality of images of bypass grafts because of the lower dependence on heart-rate variation, due to their relative spatial fixation and independence from heart contraction. Indeed although some graft segments evaluated at high heart rate presented some slight misalignment, these minor artifacts did not prevent correct evaluation of bypass patency. Diagnostic accuracy of CABG evaluation was very high (sensitivity 100%, specificity 98%), in agreement with previous reports [29–33]. Indeed, all 45 significant stenosis of grafts detected by invasive coronary angiography were correctly diagnosed by MDCT, with three cases of mild disparity in terms of the severity of the lesion observed in two segments of venous grafts.

Therefore, in the evaluation of bypass grafts correct patient preparation with beta-blocker therapy is less relevant. On the contrary good preparation (correct breathing instructions, optimized beta blocker therapy) is essential for evaluating native coronary arteries, making it possible to reach a very high quality and feasibility of scans and better diagnostic accuracy.

Limitations of the study

Consensus statement for cardiac CT appropriateness criteria has been recently published [34]. Based on these criteria several patients included in our study have not appropriate indications for cardiac CT. This was mainly due to the fact that our data were collected before the publication of these guidelines and the majority of indications for CT were posed by the referring physicians. Nowadays we are restricting indications for cardiac CT, that are based not only on symptoms and risk factors, but also on functional non-invasive tests, particularly in cases with intermediate risk.

Not all coronary segments were evaluated by CT and compared to invasive data. In particular segments <1.5 mm and segments proximal to the graft anastomosis were excluded from the analysis. However, these limitations do not detract much from our conclusions since generally pathology of these segments (including mainly distal minor branches) have little impact on clinical decisions.

References

1. Scanlon P, Faxon D, Audet A et al (1999) Society for Cardiac Angiography and Interventions. ACC/AHA guidelines for coronary angiography: a report of the American College of Cardiology/American Heart Association Task Force on practice guidelines (Committee on Coronary Angiography). J Am Coll Cardiol 33:1756–1824
2. Bashore TM, Bates ER, Berger PB et al (2001) American College of Cardiology/Society for Cardiac Angiography and Interventions Clinical Expert Consensus Document on cardiac catheterization laboratory standards: a report of the American College of Cardiology Task Force on Clinical Expert Consensus Documents. J Am Coll Cardiol 37:2170–2214
3. Hoffmann U, Hadvar J, Dunn E (2004) Is CT angiography ready for prime time? A meta-analysis. J Am Coll Cardiol 43(suppl A):312A
4. Traversi E, Bertoli G, Barazzoni G et al (2004) Noninvasive coronary angiography with multislice computer tomography. Technology, methods, preliminary experience and prospects. Ital Heart J 5(2):89–98
5. Nieman K, Cademartiri F, Lemos PA et al (2002) Reliable noninvasive coronary angiography with fast submillimeter multislice spiral computed tomography. Circulation 106:2051–2054
6. Ropers D, Baum U, Pohle K et al (2003) Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. Circulation 107: 664–666

7. Mollet NR, Cademartiri F, Nieman K et al (2004) Multislice spiral computed tomography coronary angiography in patients with stable angina pectoris. J Am Coll Cardiol 43: 2265–2270
8. Kuetter A, Kopp AF, Schroeder S et al (2004) Diagnostic accuracy of multidetector computed tomography coronary angiography in patients with angiographically proven coronary artery disease. J Am Coll Cardiol 43: 831–839
9. Leber AW, Knez A, Becker A et al (2004) Accuracy of multidetector spiral computed tomography in identifying and differentiating the composition of coronary atherosclerotic plaques. J Am Coll Cardiol 43: 1241–1247
10. Achembach S, Ropers D, Hoffmann U et al (2004) Assessment of coronary remodeling in stenotic and nonstenotic coronary atherosclerotic lesions by multidetector spiral computed tomography. J Am Coll Cardiol 43:842–847
11. Hoffmann U, Moselewski F, Cury R et al (2004) Predictive value of 16-slice multidetector spiral computed tomography to detect significant obstructive coronary artery disease in patients at high risk for coronary artery disease. Circulation 110:2638–2643
12. Cademartiri F, Marano R, Luccichenti G et al (2004) Anatomia normale del circolo coronarico con tomografia computerizzata multistrato a 16 canali. Radiol Med 107:11–23
13. Desjardins B, Kazerooni EA (2004) ECG-gated cardiac CT. AJR 182:993–1010
14. Achamnbach S, Moselewski F, Ropers D et al (2004) Detection of calcified and noncalcified coronary atherosclerotic plaque by contrast-enhanced submillimeter multidetector spiral computed tomography. Circulation 109:14–17
15. Kopp AF, Schroeder S, Kuettner A et al (2002) Noninvasive coronary angiography with high resolution multidetector-row computed tomography. Results in 102 patients European Heart Journal 23:1714–1725
16. Ferencik M, Moselewski F, Ropers D et al (2003) Quantitative parameters of image quality in multidetector spiral computed tomographic coronary imaging with submillimeter collimation. Am J Cardiol 92:1257–1262
17. Schroeder S, Kopp AF, Kuettner A et al (2002) Influence of heart rate on vessel visibility in noninvasive coronary angiography using new multislice computed tomography. Experience in 94 patients. Clin Imaging 26:106
18. Cademartiri F, Mollet NR, Runza G et al (2006) Diagnostic accuracy of multislice computed tomography coronary angiography is improved at low heart rates. Int J Cardiovascular Imaging 22:101–105
19. Austen WG, Edwards JE, Frye RL et al (1975) A reporting system on patients evaluated for coronary artery disease. Report of the Ad Hoc Committee for grading of coronary artery disease, Council of Cardiovascular Surgery, American Heart Association. Circulation 51:35–40
20. Yamashita Y, Komohara Y, Takahashi M et al (2000) Abdominal helical CT: evaluation of optimal doses of intravenous contrast material–a prospective randomized study. Radiology 216:718–723
21. Cademartiri F, Mollet N, van der Lugt A et al (2004) Non-invasive 16-row multislice CT coronary angiography: usefulness of saline chaser. Eur Radiol 14:178–183
22. Garcia MJ, Lessick J (2006) Hoffmann MHK for the CATSCAN Study Investigators. Accuracy of 16-row multidetector computed tomography for the assessment of coronary artery stenosis. JAMA 296:403–411
23. Sung SS, Yookyung K, Soo Mee L (2005) Improvement of image quality with beta-blocker premedication on ECG-gated 16-MDCT coronary angiography. AJR 84:649–654
24. Singh BN (2005) Beta-Adrenergic blockers as antiarrhythmic and antifibrillatory compounds: an overview. J Cardiovasc Pharmacol Ther 10(Suppl 1):S3–S14
25. Haverkamp V, Hindriks G, Gulker H (1990) Antiarrhythmic properties of beta-blockers. J Cardiovasc Pharmacol 16(Suppl 5):S29–S32, Review
26. Achenbach S, Ropers D, Kuettner A et al (2006) Contrast-enhanced coronary artery visualization by dual-source computed tomography-initial experience. Eur J Radiol 57(3):331–335
27. Martuscelli E, Romagnoli A, D'Eliseo A et al (2004) Evaluation of Venous and Arterial Conduit Patency by 16-Slice Spiral Computed Tomography. Circulation 110:3234–3238
28. Brundage BH, Lipton MJ, Herfkens RJ et al (1980) Detection of patent artery bypass grafts by computed tomography: a preliminary report. Circulation 61:826–831
29. Salm LP, Bax J, Jukem JW et al (2005) Comprehensive assessment of patients after coronary artery bypass grafting by 16-detector-row computed tomography. Am Heart J 150:775–781
30. Ropers D, Ulzheimer S, Wenkel E et al. (2001) Investigation of aortocoronary artery bypass grafts by multislice spiral computed tomography with electrocardiographic-gated image reconstruction. Am J Cardiol 88(7):792–795
31. Anders K, Baum U, Schmid M et al. (2006) Coronary artery bypass graft (CABG) patency: assessment with high resolution submillimeter 16-slice multidetector-row computed tomography (MDTC) versus coronary angiography. Eur J Radiol 57(3):336–344
32. Marano R, Storto ML, Maddestra N et al (2004) Noninvasive assessment of coronary artery bypass graft with retrospectively ECG-gated four-row multi-detector spiral computed tomography. Eur J Radiol 14:1353–1362
33. Rossi R, Chiurlia E, Ratti C et al (2004) Noninvasive assessment of coronary artery bypass graft patency by multislice computed tomography. Ital Heart J 5(1):36–41
34. Hendel RC, Patel MR, Kramer CM, Poon M et al (2006) American College of cardiology foundation quality strategic directions committee appropriateness criteria working group; American College of Radiology; Society of Cardiovascular Computed Tomography; Society for Cardiovascular Magnetic Resonance; American Society of Nuclear Cardiology; North

American Society for Cardiac Imaging; Society for Cardiovascular Angiography and Interventions; Society of Interventional Radiology. ACCF/ACR/SCCT/SCMR/ASNC/NASCI/SCAI/SIR 2006 appropriateness criteria for cardiac computed tomography and cardiac magnetic resonance imaging: a report of the American College of Cardiology Foundation Quality Strategic Directions Committee Appropriateness Criteria Working Group, American College of Radiology, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, American Society of Nuclear Cardiology, North American Society for Cardiac Imaging, Society for Cardiovascular Angiography and Interventions, and Society of Interventional Radiology. J Am Coll Cardiol 48(7):1475–1497