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Year: 2010

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## Dual-step prospective ECG-triggered 128-slice dual-source CT for evaluation of coronary arteries and cardiac function without heart rate control: a technical note

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**Abstract:** **PURPOSE:** To describe prospective ECG-triggered dual-source CT dual-step pulsing (pECG(dual\_step)) for evaluation of coronary arteries and cardiac function. **METHODS:** Fifty-one consecutive patients pre- or post-cardiovascular surgery were examined with adaptive sequential tube current modulated (pECG(dual-step)) 128-slice dual-source CT without heart rate control (main padding window: 40% RR interval >65 bpm/70% RR interval <65 bpm). Image quality of coronary arteries was graded (4-point scale), and cardiac function was evaluated. **RESULTS:** Mean HR was 68 bpm. Thirty-seven patients were in stable sinus rhythm (SR); 14 had arrhythmia. Image quality of coronary arteries was diagnostic in 804/816 (98%) of segments. The number of non-diagnostic segments was higher in patients with arrhythmia as compared to those in SR (4% vs. 0.5%;  $p = 0.01$ ), and there were fewer segments with excellent image quality (79% vs. 94%;  $p < 0.001$ ) and more segments with impaired image quality ( $p < 0.001$  and  $p = 0.002$ ). Global and regional LV function could be evaluated in 41 (80%) and 47 (92%) patients, and valvular function in 48 (94%). In 11/14 of patients with arrhythmia, the second step switched to full mAs, increasing radiation exposure to 8.6 mAs ( $p < 0.001$ ). The average radiation dose was 3.8 mSv (range, 1.7-7.9) in patients in SR. **CONCLUSION:** pECG(dual-step)128-slice DSCT is feasible for the evaluation of coronary arteries and cardiac function without heart rate control in patients in stable sinus rhythm at a low radiation dose.

DOI: <https://doi.org/10.1007/s00330-010-1794-7>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-33640>

Journal Article

Published Version

Originally published at:

Feuchtner, G; Götti, R; Plass, A; Baumueller, S; Stolzmann, P; Scheffel, H; Wieser, M; Marincek, B; Alkadhi, H; Leschka, S (2010). Dual-step prospective ECG-triggered 128-slice dual-source CT for evaluation of coronary arteries and cardiac function without heart rate control: a technical note. *European Radiology*, 20(9):2092-2099.

DOI: <https://doi.org/10.1007/s00330-010-1794-7>

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## Dual-step prospective ECG-triggered 128-slice dual-source CT for evaluation of coronary arteries and cardiac function without heart rate control: a technical note

Received: 20 November 2009  
Revised: 21 February 2010  
Accepted: 24 February 2010  
Published online: 21 April 2010  
© European Society of Radiology 2010

Electronic supplementary material  
The online version of this article (doi:10.1007/s00330-010-1794-7) contains supplementary material, which is available to authorized users.

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**Abstract:** *Purpose:* To describe prospective ECG-triggered dual-source CT dual-step pulsing (pECG<sub>dual-step</sub>) for evaluation of coronary arteries and cardiac function. *Methods:* Fifty-one consecutive patients pre- or post-cardiovascular surgery were examined with adaptive sequential tube current modulated (pECG<sub>dual-step</sub>) 128-slice dual-source CT without heart rate control (main padding window: 40% RR interval >65bpm/70% RR interval <65bpm). Image quality of coronary arteries was graded (4-point scale), and cardiac function was evaluated. *Results:* Mean HR was 68bpm. Thirty-seven patients were in stable sinus rhythm (SR); 14 had arrhythmia. Image quality of coronary arteries was diagnostic in 804/816 (98%) of segments. The number of non-diagnostic segments was higher in patients with arrhythmia

as compared to those in SR (4% vs. 0.5%;  $p=0.01$ ), and there were fewer segments with excellent image quality (79% vs. 94%;  $p<0.001$ ) and more segments with impaired image quality ( $p<0.001$  and  $p=0.002$ ). Global and regional LV function could be evaluated in 41 (80%) and 47 (92%) patients, and valvular function in 48 (94%). In 11/14 of patients with arrhythmia, the second step switched to full mAs, increasing radiation exposure to 8.6mAs ( $p<0.001$ ). The average radiation dose was 3.8mSv (range, 1.7–7.9) in patients in SR. *Conclusion:* pECG<sub>dual-step</sub> 128-slice DSCT is feasible for the evaluation of coronary arteries and cardiac function without heart rate control in patients in stable sinus rhythm at a low radiation dose.

**Keywords** Computed tomography · Coronary arteries · Cardiac function · Prospective ECG triggering · Radiation dose

### Introduction

Prospective ECG-triggering (pECG) using sequential (“step-and-shot”) mode [1–7] is an effective imaging technique in coronary computed tomography (CT) angiography permitting low radiation exposure ranging between 2.5–4.3 mSv [1–7] with radiation dose savings ranging

between 77–79% [5, 6] as compared to conventional retrospective helical ECG gating. However, pECG triggering is restricted to diastolic CT image acquisition; hence, only patients with low (<65–70 bpm) and regular heart rates [1–7] can be examined. Due to the lack of systolic data, the evaluation of cardiac function such as regional and global left ventricular (LV)-function or valvular function is not possible. Left ventricular global [8, 9] and regional function

analysis is feasible with CT [10–13]. Regional wall motion abnormalities are indicators of ischemic heart disease, and their evaluation, complementary to coronary CTA, can help to diagnose coronary artery disease. Further, native or prosthetic valves may be studied by CT in selected patients for specific reasons [14–17].

A new 128-slice dual-source CT [18–21] system has been introduced recently, providing the high-pitch spiral (“flash”) mode [18–21], which however necessitates a low heart rate of <60 bpm as well [20]. This 128-slice dual-source CT is equipped with a new pECG-triggered module, namely the “dual-step” pulsing (pECG<sub>dual-step</sub>), encompassing some novelities for dual-source CT: First, a second pulsing window operating at tube current mAs reduced to 20% can be stretched over the entire cardiac cycle. Second, the first major pulsing window (at full tube current mAs) can be set at any arbitrary time point of cardiac cycle, allowing for systolic image acquisition, as recommended in patients with high heart rates [22]. Further, the second pulsing window is triggered by the occurrence of arrhythmia to switch automatically to full tube current exposure during the entire cardiac cycle to ensure optimal image quality in patients with irregular heart beats. Finally, temporal resolution of the 128-slice CT scanner is improved to 75 ms by using 0.28-s gantry rotation. These technical features could allow for evaluation of coronary arteries irrespective of heart rate, including a comprehensive evaluation of regional and global LV function.

Therefore, the aim of this feasibility study was to explore the new prospective “step-and-shot” ECG-triggered “dual-step” (pECG<sub>dual-step</sub>) mode using 128-dual-source CT in consecutive patients without heart rate control, before or after cardiac or cardiovascular surgery, regarding image quality of coronary arteries and complementary evaluation of cardiac and valvular function.

## Materials and methods

### Study population

Fifty-one consecutive patients (Table 1) who underwent clinically indicated CT angiography before or after cardiac or cardiovascular surgery were examined between June 2009 and October 2009.

Patients with elevated heart rates and arrhythmia were not excluded. No additional premedication for heart rate control was added to the patients’ baseline medications.

General exclusion criteria for contrast-enhanced CT were nephropathy (defined as a serum creatinine level above 150  $\mu\text{mol/l}$ ) and known hypersensitivity to iodine-containing contrast media.

### CT data acquisition and post-processing

All examinations were performed using a second-generation dual-source CT system (Somatom Definition Flash,

**Table 1** Study population (51 patients)

	pECG <sub>dual-step</sub> n=51
Age (years)	61±12 (range, 30–83)
Gender	
Males (n, %)	34 (66.6%)
Heart rate (bpm)	67.2±9.9 (range, 51–98)
>65 bpm: 40% of RR (n, %)	25 (49%)
<65 bpm: 70% of RR (n, %)	26 (51%)
Heart rhythm	
Sinus rhythm (n, %)	47 (92%)
Without PVC	37 (72.5%)
With PVC	10 (20%)
Atrial fibrillation (n, %)	4 (8%)
Clinical status	
Before cardiovascular surgery	24 (47%)
Aortic valve	6
Mitral valve	4
CABG	5
Misc. (e.g., EAP; combined aortic valve/root; Ross procedure, etc.)	9
After cardiovascular surgery	27 (53%)
Mechanic prosthetic	13
Bioprosthetics	6
CABG	3 <sup>a</sup>
Misc. (e.g., EAP)	6
BMI (kg/m <sup>2</sup> )	25±4.6 (range, 16.7–39.1)

<sup>a</sup> There was one patient after combined prosthetic and CABG surgery

Siemens Healthcare, Forchheim, Germany). In each patient, 80 ml of iopromide (Ultravist 370, 370 mg/ml, Bayer Schering Pharma, Berlin, Germany) was injected at a flow rate of 5 ml/s followed by 60 ml saline solution. Contrast agent application was controlled by bolus tracking in the ascending aorta (signal attenuation threshold 100 HU). The delay after reaching the threshold to the initiation of the CT scan was 10 s. Patients were advised to hold their breath during the scan. Scanning parameters were: slice collimation 2×128×0.6 mm by means of a z-flying focal spot, gantry rotation time 280 ms, and tube potential 100 kV or 120 kV based on a body mass index (BMI) cutoff of 25 kg/m<sup>2</sup> [23, 24]. Attenuation-based tube current modulation was used with a reference tube current-time product set at 320 mAs per rotation. A cranio-caudal scan direction was chosen, and the start phase for image acquisition was selected manually at the level of the pulmonary artery bifurcation and stopped at the base of the heart. The full tube current window was selected at 40% of the R-R interval if the heart rate was >65 bpm and at 70% if the heart rate was <65 bpm. The second tube current window, reduced to 20% of the nominal output, was selected from 10–90% of the R-R interval.

Images were reconstructed with a slice thickness of 0.75 mm and an increment of 0.5 mm, using a medium smooth tissue convolution kernel (B26f) at 5% increments throughout the cardiac cycle (10–90% of RR interval).

All images were anonymized and transferred to an external workstation (Multi-Modality Workplace, Siemens Healthcare, Forchheim, Germany). The phase with best image quality of coronary arteries was selected for readout of coronary arteries. First, the image quality of the coronary

arteries was evaluated on a per-segment basis (modified AHA 16-segment classification) using interactive oblique multiplanar reformations by two experienced independent observers with 6 years of experience in cardiac CT (G.F.) and 1 year of experience (R.G.) on a 4-point scale: 1, excellent (no artifacts); 2, good (minor artifacts); 3, mediocre (artifacts but still diagnostic); 4, poor (severe artifacts rendering image quality non-diagnostic). A consensus read-out was appended in case of disagreement, and the consensus results were taken for final data analysis.

Second, global left ventricular function was measured with dedicated software (Syngo Circulation, Siemens) allowing for computation of left ventricular end systolic volume (ESV), end diastolic volume (EDV), stroke volume (SV) and the ejection fraction (EF). Specific reasons for insufficient evaluations were noted. Then, 4D cine image series were reviewed using the cine mode on Circulation (Syngo, Siemens) on three planes (four-, three- and two-chamber views). The evaluation of regional wall motion abnormalities (WMA) was scored as “assessable” or “non-assessable.” Valvular function was reviewed as well, during both systole and diastole, and the aortic valve (native or prosthetic) leaflets were scored as “assessable” or “non-assessable” on cross-sectional short axis views of the valve and aortic root as derived from left coronal and left sagittal planes through the aortic root. Specific reasons for non-assessability (e.g., type of artifacts) were noted. For all evaluations, consensus reading was performed. The effective radiation dose delivered at thoracic CT was calculated applying a method proposed by the European Working Group for Guidelines on Quality Criteria for CT [25] using the dose-length product (DLP) and a conversion coefficient for the chest of 0.017 mSv/[mGy × cm]. The DLP was obtained from an electronic protocol that summarized the individual radiation exposure parameters of each CT acquisition.

## Statistical analyses

All statistical analyses were performed by commercially available software (SPSS, release 17, SPSS Inc., Chicago, IL). Continuous variables were expressed as means ± standard deviations or as medians and ranges. Categorical variables were expressed as frequencies (counts) or percentages.

Inter-observer agreement for qualitative image quality ratings was evaluated using Cohen’s kappa statistics. A  $\kappa$  value greater than 0.81 was interpreted as excellent agreement, values of 0.61–0.80 were interpreted as good, values of 0.41–0.60 as moderate, values of 0.21–0.40 as fair and values less than 0.20 as poor agreement.

The image quality scores between patients in regular sinus rhythm and those with arrhythmia were tested separately (for each score) for differences with the chi-square test or Fisher’s exact test. Differences in radiation dose and heart rate between patients with regular sinus rhythm and arrhythmia were tested with the independent t-test.

Differences in image quality scores between patients in whom coronary arteries were evaluated during systole (at 40% of the R-R interval) or during diastole (at 70% of the RR interval) were tested with the Mann-Whitney U-test. A p-value below 0.05 was considered statistically significant.

## Results

A total of 51 patients were successfully examined with the pECG<sub>dual-step</sub> technique. Table 1 shows patient profiles, including reason for referral to CT angiography. Mean heart rate was 67 bpm. In 25 (49%) patients, the first pulsing window was set at 70% of the RR interval and in 26 patients (51%) at 40%, respectively. Of the 51 consecutive patients, 37 (73%) had stable sinus rhythm (SR) without arrhythmia, and 14 (27%) patients had arrhythmia [n=4, atrial fibrillation (AF); and n=10, extrasystole].

### Coronary arteries

A total of 816 coronary segments were analyzed. Of these, 733 (89.8%) had excellent image quality (Fig. 1) 56 (7%) segments had good and 15 (1.8%) had mediocre image quality. Twelve of 816 (1.5%) segments were non-diagnostic in 9 patients; of these, 6 had arrhythmia. The main reason for non-diagnostic segments was misregistration artifacts based on “step” artifacts (n=9) leading to missing parts of the artery (n=4), or severely hampered image quality (n=5) in combination with blurring and streak artifacts, or motion blurring artifacts (n=3, of those in one segment combined with high image noise). Interobserver agreement was excellent with  $K=0.84$ .

If dividing patients into two groups (SR, n=37 and arrhythmia, n=14; Table 2), the number of non-diagnostic segments (n=9) was significantly higher in patients with arrhythmia as compared to those without (n=3; 4% vs. 0.5%;  $p=0.01$ ), and the number of segments with excellent image quality was significantly lower (79% vs. 94%,  $p<0.001$ ). The number of segments with impaired image quality (score 2 and 3) was significantly higher in patients with arrhythmia (11.6% vs. 5.1% and 5.4% vs. 0.5%;  $p<0.001$  and  $p=0.002$ ), respectively.

There was no difference in image quality scores between patients in which coronary arteries were evaluated at 40% and 70% of the RR interval (mean score  $1.18\pm 0.24$  and  $1.12\pm 0.32$ ;  $p=0.301$ ).

### Global LV function, regional WMA and valvular function

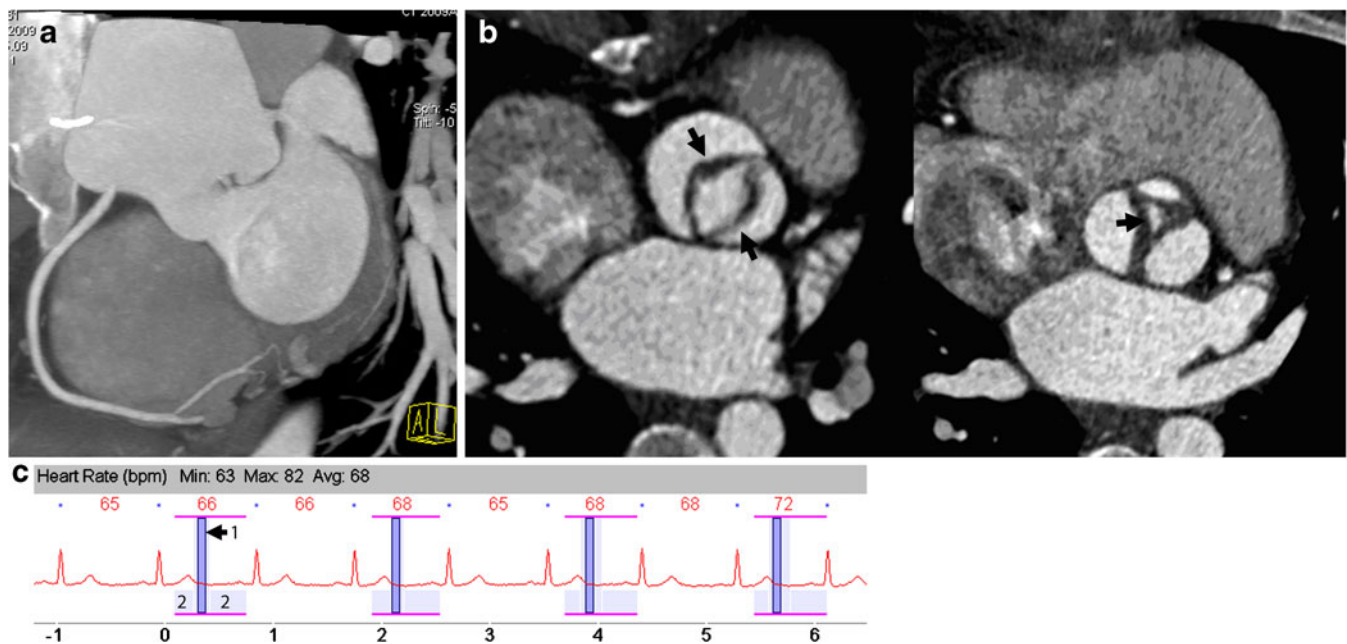
Quantification of LV function was successful and chamber segmentation regarded as accurate in 42/51 (80%) of patients. Mean LV-EDV was 134 ml, mean LV-ESV was 64.8 ml, mean SV was 69.2 and mean EF 52.9%. In eight patients, low LV contrast attenuation and/or high image

**Table 2** Performance of pECG<sub>dual-step</sub> module in 51 patients: CT image quality (IQ) of coronary arteries, cardiac function and radiation dose. Comparison of patients in stable sinus rhythm (SR) with those having arrhythmia

	Patients in stable SR 37 patients	Patients with arrhythmia (AF, PVC) 14 patients	p-value
IQ coronary arteries	(N=592 segments)	(N=224 segments)	
Diagnostic			
Score 1	556 (94%)	177 (79%)	P<0.001 <sup>c</sup>
Score 2	30 (5.1%)	26 (11.6%)	P=0.002 <sup>b</sup>
Score 3	3 (0.5%)	12 (5.4%)	P<0.001
Non-diagnostic			
Score 4	3/592 (0.5%)	9/224 (4%)	P=0.01 <sup>a</sup>
Cardiac function			
Global LV function	41/51 (80%)		
Regional LV function	47/51 (92%)		
Valvular function	48/51 (94%)		
Native	31/32 (96%)		
Prosthetics	17/19 (89%) <sup>c</sup>		
Second step: tube current modulation at 20% mAs			
n (%)	37/37 (100%)	3/ 14 (21%)	<0.001
Second step at 20% mAs?	Yes: 40 patients	No: 11 patients	
Radiation dose (mSv)	3.8±1.6	8.6±3.1	<0.001
Heart rate (bpm)	66.2±8	70±15	0.194
BMI	26±5	25.4±5	0.708
Effective radiation dose (mSv)	3.8±2	7.9±3	<0.001
	4.9±3 mSv (range, 1.7–14)		

<sup>a</sup> Fisher's exact test; <sup>b</sup> chi-square IQ score 1 (excellent), score 2 (good) and score 3 (mediocre) were regarded as diagnostic, whereas score 4 was considered non-diagnostic. AF = atrial fibrillation; PVC = premature ventricular contraction; LV = left ventricle; BMI = body mass index; n = counts; bpm = beats per minute; mSv = milli-Sievert

<sup>c</sup> Both non-evaluable prosthetic valves were miniroot bioprosthesis (same type)



**Fig. 1** **a** Coronary arteries in pECG<sub>dual-step</sub> mode: 38 YOF in sinus rhythm (heart rate, 68 bpm) before redo aortic valve surgery. Excellent image quality of coronary arteries: note right coronary artery (RCA) permitting preoperative rule out of coronary stenosis. The first pulsing window was set at 40% of the RR interval. Beta-blockers were contraindicated because of aortic stenosis. Radiation dose was 2.23 mSv. **b** Valvular function: Combined moderate aortic stenosis (left panel, early systole: arrows denote aortic valve orifice area, “fish mouth” opening of bicuspid valve) and severe regurgitation (right panel, end diastole: note incomplete closure of

thickened cusps). Late recurrence of valvular dysfunction after congenital aortic stenosis surgery. The corresponding movie shows opening of bicuspid valve and closure with incompetent cusps. The systolic image (left) was derived from 4D cine loops at 15% of RR interval and the diastolic image (right) at 70%. **c** pECG<sub>dual-step</sub> module; ECG during scan: 1=first pulsing window at 40% of RR interval (100% mAs) (arrow). 2=second pulsing window from 10–90% of the RR interval covering the entire cardiac cycle (tube current reduced to 20% of full mAs)

noise, and in one patient stair-step artifacts led to insufficient chamber segmentation results.

On 4D cine images, regional WMA analysis was assessable in 47/51 (92%) patients. Reasons for non-assessability were: low LV contrast attenuation (n=2), stair-step artifacts (n=1) and high image noise (n=1) in the second step phase (diastole), respectively.

Valvular function was assessable in 48/51 patients (94%) during both systole and diastole (Fig. 1b, c). One native valve was non-assessable because of stair-step artifacts caused by arrhythmia during both phases. There were 19 prosthetic valves, of which 17 could be evaluated, but in 2 miniroot bioprosthetic valves, the leaflets were not adequately delineated because of high image noise during the second pulsing phase (n=1 systole, n=1 diastole). However, valve morphology could be evaluated in the counterpart phase of the cardiac cycle at 100% mAs exposure. In two further native valves, image noise during the second step pulsing window phase of the cardiac cycle (either systole or diastole) had excessive image noise hampering the evaluation.

#### pECG<sub>dual-step</sub> technical performance evaluation

The second step switched from 20% up to 100% tube current mAs in 11/14 (79%) of patients with arrhythmia (AF, n=4

and SR with extrasystole in n=7) (Fig. 2). In these 11 patients, the radiation dose was significantly ( $p<0.001$ ) higher with  $8.6 \text{ mAs} \pm 3.1$  compared to those patients in whom the “dual step” worked sufficiently (mean,  $3.8 \text{ mSv} \pm 1.7$ ) (Table 2).

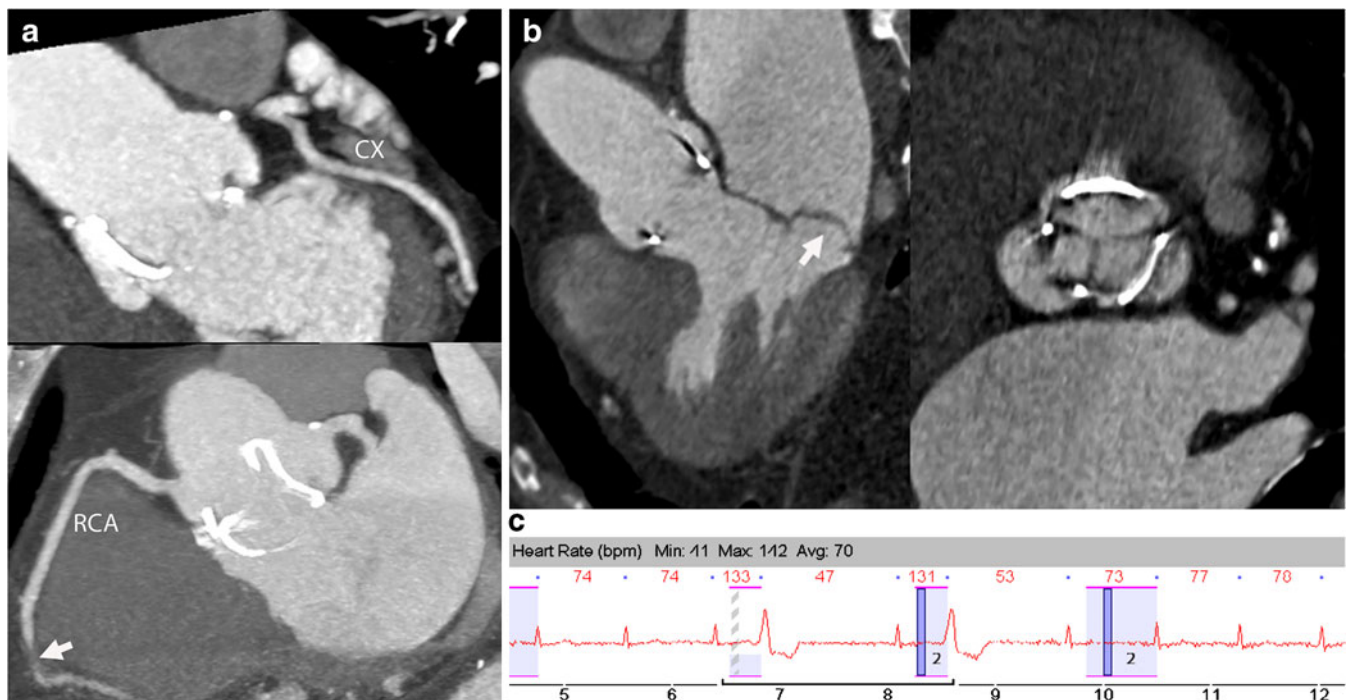
In all 37 patients without arrhythmia, the pECG<sub>dual-step</sub> mode pulsed the second window at reduced tube current mAs.

CT data were acquired within 3 heart beats (9 patients), within 4 heart beats (32 patients), within 5 steps (8 patients) or 6 steps (2 patients). Mean scan time was  $6.6 \text{ s} \pm 1.7 \text{ s}$  (3.0–10.5 s), and the time of each pulsing window was  $0.56 \pm 0.4 \text{ s}$  (0.49–1.14 s). Mean dose-length product (DLP) was  $284.5 \text{ mGy} \cdot \text{cm}$ . Mean CDTI<sub>vol</sub> was  $24.4 \text{ mGy}$ . Effective radiation dose was  $4.9 \pm 3 \text{ mSv}$  (range, 1.7–14).

## Discussion

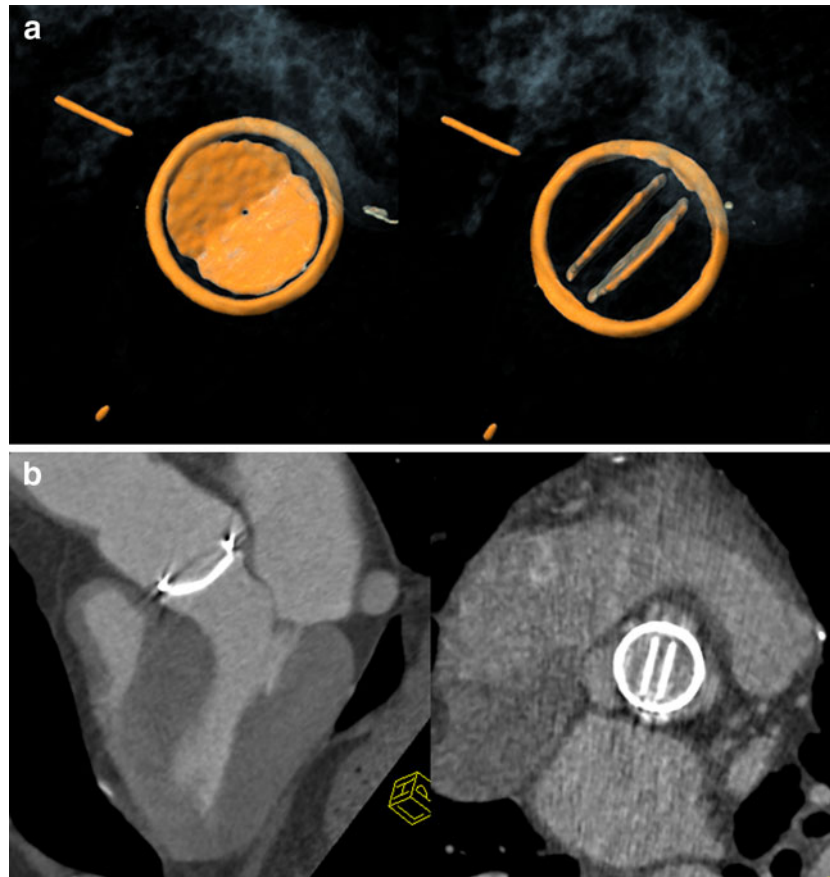
Our study shows that the new pECG<sub>dual-step</sub> module in 128-slice DSCT allows for reliable evaluation of coronary arteries and cardiac function in patients with regular heart rates without arrhythmia at a low radiation dose of 3.7 mSv.

The first advantage of the pECG<sub>dual-step</sub> module compared to conventional “step-and-shoot” protocols is



**Fig. 2** pECG<sub>dual-step</sub> in a patient with arrhythmia (atrial fibrillation and extrasystole). **a** Coronary arteries: CX (upper panel) with excellent image quality. RCA (lower panel) had one non-diagnostic coronary segment (arrow, mid segment 2) because of an artifact. Radiation exposure was 6.9 mSv. **b** Valvular function: Mitral valve prolapse of posterior cusp during systole (arrow, left panel) on three-chamber view and bioprosthetic aortic valve (right panel) on cross-sectional view during diastole. The systolic image (left) was

created from 4D cine loops at 15% of the RR interval and the diastolic image (right) at 70% of the RR interval. **c** pECG<sub>dual-step</sub> ECG during scan: The second pulsing step (2) skipped the second beat (133 bpm) and was operating on full 100% mAs at the next two beats (131 bpm and 73 bpm) instead of reduced tube current to ensure diagnostic image quality of coronary arteries. Note atrial fibrillation and multiple ventricular extrasystoles



**Fig. 3** Movie 2. Evaluation of mechanical prosthetic valve. **a** Volume-rendered 3D images of mechanic prosthetic St. Jude bileaflet valve. Diastole (left), closed. Systole (right), open. **b** Multiplanar reformations (MPR). Three-chamber view (left) during diastole shows normal closed mechanic valves, and cross-sectional view

(right) during systole shows normal opening. Note higher image noise during systole (right) because of tube current modulation during the second step, which did not hamper evaluation of prosthetic valve function (see movie 2)

the possibility of its application irrespective of the height of the heart rate. To date, the use of prospective ECG triggering has been recommended in low heart rates <65–70 bpm [1–7, 30] only because the image acquisition (“padding”) window had to be placed at diastole. The pECG<sub>dual-step</sub> module allows for a placing of the main first padding window at any arbitrary time point of the cardiac cycle, including the systole. Hence, we explored the use of 40% of the RR interval in patients with a baseline heart rate of more than 65 bpm. Our data confirm good diagnostic image quality of coronary arteries during the end-systolic phase in patients with a regular heart rate, which is in line with reports from retrospective ECG gating [22]. At higher heart rates, the diastole shortens more compared to systole; thus, the end systole is a more appropriate phase for image acquisition. Additional medication with beta-blockers to lower to the heart rate before performing the CT scan can be avoided. In clinical practice, some patients may not respond to beta-blockers or the use of beta-blockers is contraindicated, such as in patients with severe aortic stenosis or LV dysfunction. However, we observed a significantly worse image quality of coronary segments in patients with arrhythmia, both in

those with AF and those with extrasystole, which is in line with previous studies [1–7]. Therefore, the pECG<sub>dual-step</sub> mode should be used in patients with stable sinus rhythm only.

Second, by establishing a second image acquisition window (second step) with the tube current reduced to 20%, similar to the ECG tube current modulation technique (“ECG pulsing”) [26] during the entire cardiac cycle, full functional CT data sets can be acquired. These data sets allow for calculation of global and regional left ventricular function, and evaluation of cardiac valves on 4D cine movies. Evaluation of wall motion abnormalities [9, 10] is feasible with CT, which may improve the accuracy of coronary CT angiography [13]. The evaluation of cardiac valves [14–17] for indications such as assessment of valvular morphology [15], aortic valve area measurement [14], planning of minimally invasive and percutaneous surgery [16] or prosthetic valve (Fig. 3) dysfunction [17] is possible. In our study, only in a minority of patients could LV function not be assessed either because of low contrast attenuation in the left ventricle resulting in insufficient left ventricular volume segmentation, which could have been avoided by using a

higher volume of contrast agent, or in the presence of stair-step artifacts caused by arrhythmia. High image noise at the second step was problematic in one patient only.

Valvular function could be assessed in the majority of patients, despite merging both native and prosthetic valves. The only problem was one specific prosthetic valve type, a miniroot bioprosthesis in two patients, in which the leaflets were not well delineated because of high image noise during the second pulsing phase at reduced tube current (either systole or diastole depending on the selected phase), but still morphology of leaflets could be assessed at the contrary phase of the cardiac cycle.

However, the pECG<sub>dual-step</sub> should be used in patients with regular sinus rhythm only, in the absence of arrhythmia such as premature beats, because the main reason for limited image quality was arrhythmia. In patients with arrhythmia, the second pulsing step switched into full 100% mAs exposure to ensure coronary image quality, leading to a significant increase in radiation dose, which with 8.6 mSv was however still lower than in retrospectively ECG-gated spiral scanning using 64-slice CT with 14–16 mSv and 64-slice DSCT [27–29] because of differences in image acquisition, e.g., that the amount of overranging and overscanning is reduced by using the pECG<sub>dual-step</sub> mode.

Sequential pECG-triggering using 128-slice DSCT [30] has recently shown to have a radiation exposure of 3.6 mSv when being restricted to beta-blocker medication and low heart rate of 61 bpm. The mean radiation dose in our study was similar and only slightly higher despite adding a second pulsing window at reduced tube current mAs. However, in contrast to Andres et al. [30], applying a fixed setting of 120 kV, we used a radiation dose-saving body weight-adapted tube voltage protocol (if <25 kg/m<sup>2</sup> BMI: 100 kV and if >25 kg/m<sup>2</sup> BMI: 120 kV [23, 24]).

Average radiation dose in our study using the pECG<sub>dual-step</sub> module was within the upper range of previous studies exploring “single-shot” pECG triggering on 64-slice CT with 2.5–4.3 mSv [1–7], but higher compared to the high-pitch spiral mode using 128-slice DSCT with ~1 mSv [19–21].

## Study limitations

First, we acknowledge that this was an explorative study design, since there are no reports about the pECG<sub>dual-step</sub> module so far. Therefore, we did not compare pECG<sub>dual-step</sub> with a reference standard method. Further confirmatory and comparative head-to-head studies with retrospective ECG gating in spiral mode are needed.

Second, we did not perform heart rate control by using beta-blocker medication. Possibly the performance of the pECG<sub>dual-step</sub> module, e.g., for wall motion abnormalities or valvular function, might be improved if the heart rate is lowered with beta-blockers. However, one needs to keep in mind that for accurate estimation of global LV function, beta-blocker medication is not recommended because negative inotropic effects lead to a bias. Moreover, beta-blockers might be contraindicated in patients with aortic valve stenosis or other comorbidities before or after cardiovascular surgery.

Third, we explored a selected patient population (pre- and post-cardiac surgery setting) that certainly has a higher prevalence of arrhythmia and high heart rates compared to patients usually referred to coronary CTA (e.g., those with intermediate risk of coronary artery disease).

## Conclusion

1. Using the adaptive sequential pECG<sub>dual-step</sub> mode on 128-slice DSCT is feasible for coronary artery and complementary cardiac function evaluation at low radiation exposure.
2. We suggest its application in patients in stable sinus rhythm without arrhythmia irrespective of the height of heart rate.
3. Our study suggests that placing the padding window at end systole (e.g., 40% of cardiac cycle) in patients with high heart rates of >65 bpm and at end diastole (70% of cardiac cycle) in patients with low heart rates <65 bpm provides diagnostic image quality of the coronary arteries.

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