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Radiation dose and image quality of CT coronary angiography in patients with high heart rate or irregular heart rhythm using a 16-cm wide detector CT scanner

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Abstract

Aim of the study was to evaluate the effect of high and irregular heart rate on the image quality and on the radiation exposure using a 256-row, 16-cm wide detector computed tomography (CT) system. Between March and December 2019, 349 patients undergoing CT coronary angiography (CTCA) were prospectively enrolled. Patients were divided into 2 study groups; Group 1 included patients with a regular heart rate of ≤70 bpm, while Group 2 included patients with an irregular heart rhythm or heart rate of >70 bpm. In all patients, image quality score and radiation dose were analyzed and recorded. In Group 1, there were a total of 195 patients, while in Group 2, there were 154 patients. Of the 349 patients, 299 of them had a regular heart rhythm (85.7%) and 50 (14.3%) had an irregular heart rhythm. Mean heart rate during scanning was 59 ± 7 bpm in Group 1 and 80 ± 12 bpm in Group 2. Mean effective dose of CTCA in Group 1 (1.2 ± 0.8 mSv) was lower than in Group 2 (1.9 ± 1.2 mSv, $P < .001$). Mean image quality (Likert score) of Group 1 was significantly higher than in Group 2 (4.1 vs 3.4, $P < .001$). CT scanner with 16-cm wide detector enables low-radiation exposure during CTCA even at high heart rate or irregular heart rhythm. Good CTCA image quality and low dose are related to low heart rate.

Abbreviations: ASiR-V = iterative adaptive statistical iterative reconstruction, CT = computed tomography, CTCA = computed tomography coronary angiography, DLP = dose–length product, ECG = electrocardiogram, FOV = field of view.

Keywords: computed tomography angiography, heart rate, image quality, radiation dose

1. Introduction

Computed tomography (CT) coronary angiography (CTCA) is an important noninvasive diagnostic tool for the assessment of patients with coronary artery disease. According to the most recent guidelines, CTCA is the first choice diagnostic modality in symptomatic patients suffering from coronary artery disease.[1,2] The main disadvantages of CTCA represent 2 factors, such as radiation dose and motion artifacts with low image quality. Several factors impact the quality of the CT image, including both the CT scanner and the patient. From the patient standpoint, the heart rate has the most significant influence on the quality of the scan.[3] With an increased heart rate or arrhythmia, the image quality decreases while the radiation exposure increases.[4] According to the European Society of Cardiology Guidelines from 2019, CTCA is not recommended in patients with an irregular heart rhythm, an extensive calcium score, or severe obesity.[1] In the past, CTCA was associated with high radiation dose for the patients which could potentially lead to radiation induced cancer. The widespread use of CTCA in the medical field was made possible by significant technological advancements.[5–7] The data show that CTCA leads to greater uptake of preventive measures than usual care among patients with stable chest pain symptoms, and this new economic model suggests, it is cost-effective over a patients' lifetime compared with functional-based stress testing.[8–10] In recent years, several predominantly single-centered studies have been conducted that have shown high image quality and relatively low-radiation exposure even in patients with an increased heart rate or atrial fibrillation.[11–17] The aim of our study was to evaluate the effect of heart rate and rhythm on the image quality and on the radiation dose of CTCA using a 256-row, 16-cm wide detector CT system.

2. Materials and Methods

2.1. Study population

From March 2019 to December 2019, a total of 349 patients undergoing CTCA were prospectively enrolled in the study at the Department of Radiology in University Hospital Trnava,

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The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Slovakia. There were no exclusion criteria based on heart rate frequency or calcium score. Patients with a heart rate of >70 bpm and without any known contraindications to beta-blockers, such as chronic obstructive pulmonary disease, severe peripheral vascular disease, and asthma, were intravenously administered 1 mg/kg of the beta-blocker esmolol (Esmocard, Orphan Pharmaceuticals AG, Vienna, Austria). No oral beta blockers were given. Each patient received sublingual nitrates (Isoket, Aesica Pharmaceuticals GmbH) just prior to being examined. We divided the patients into 2 study groups; the first group included patients with a regular heart rate of ≤70 bpm, while the second group included patients with an irregular heart rhythm or heart rate of >70 bpm. The irregular heart rhythm was defined as irregular R-R intervals diagnosed with ECG. Every patient signed an informed consent form before undergoing the CT scan. The study was approved by the Local Ethics Committee of University Hospital Trnava.

2.2. Imaging protocol

All patients were examined on a CT scanner with 16-cm diameter detector (Revolution CT, GE Healthcare, Milwaukee, WI) with the following parameters: 256 × 0.625 mm collimation, gantry rotation speed of 280 ms, 0.23 mm spatial resolution, and prospective electrocardiographic triggering. Native calcium scores were performed in all patients (except in patients with bypass graft or implanted stent) according to protocol: field of view (FOV) width 25 cm, X-ray voltage 120 kV, automatic current modulation 50 to 350 mA, and with prospective ECG scanning at 75% phase of 1 R-R interval. Calcium score was measured in the standard method with the Agatston score. The scanning parameters of the CTCA protocol included:

- Tube potential of 100 kV for patients weighing <100 kg, 120 kV for patients weighing >100 kg.
- Automatic adjustment of the tube current in the range of 200 to 700 mA, so that the same noise index is achieved in all patients.
- Length of the scanned area 12 to 16 cm, depending on the size of the heart, per gantry rotation. In patients after coronary artery bypass grafting, the scan area was extended to the full chest height, to 2 gantry rotations.
- Patients with regular heart rate of ≤70 bpm were scanned in diastolic phase 70% to 80% of 1 R-R interval on ECG (Group 1).
- Patients with a heart rate of >70 bpm or irregular heart rhythm were scanned in end systolic phase (30%–50%) and diastolic phase (70%–80%) of 1 heart cycle (Group 2).
- Iterative adaptive statistical iterative reconstruction (ASiR-V) algorithm was used for image reconstruction.
- Patients below 100 kg received 65 mL of contrast agent through an 18-G cannula at a rate of 5 mL/s followed by a 50 mL saline solution. Patients over 100 kg or patients with stitched bypasses received 85 mL of contrast agent.
- Triggering a scan based on a visual assessment of no amount of contrast in the right ventricle.

2.3. Analysis and interpretation of examination

All examinations were independently evaluated by 2 experienced radiologists on special cardio software (CardIQ Xpress). For each CTCA examination, its image quality for all main coronary arteries was determined on a 5-degree "Likert" scale: 5 = excellent quality, no artifacts; 4 = good quality, with minor artifact; 3 = average quality acceptable for routine diagnosis; 2 = below-average quality, but examination is still evaluable; 1 = insufficient quality, nondiagnostic examination.

2.4. Radiation dose parameters

For each examination, the radiation load as dose–length product (DLP) was measured in

mGy·cm. The effective dose was calculated using the chest-specific conversion factor according to the formula (K = 0.014 mSv/mGy·cm)[18] The radiation dose was calculated for the whole examination (planning topograms + native calcium score examination + planning and monitoring scans + CTCA) and especially for CTCA alone.

2.5. Statistical analysis

Results were evaluated statistically with SPSS 26.0 statistical package (IBM SPSS, Chicago, IL). The descriptive statistics of patient data are summarized as the mean ± standard deviation (mean and 95% confidence interval for mean) for continuous variables and frequency (percentage) for categorical variables. The Shapiro–Wilk test was used to verify the normal distribution of the analyzed data. The 1-way analysis of variance with Tukey HSD posttest was used to determine the significant differences between 3 or more groups. The independent samples *t* test was used to determine the significant differences between 2 groups. The differences between categorical variables were analyzed by Pearson χ^2 test. *P* values ≤.05 were considered to indicate significant differences.

3. Results

3.1. Baseline characteristics

In the study period, 349 patients underwent CTCA, 201 were male (57.6%). In Group 1, there were a total of 195 patients, while in Group 2, there were 154 patients. Of the 349 patients, 299 of them had a regular heartbeat (85.7%) and 50 (14.3%) had an irregular heartbeat. A calcium score was established in every patient without a prior diagnosis of ischemic heart disease (334 patients), while the remaining 15 patients had either undergone prior coronary artery bypass surgery (9 patients) or stent insertion (6 patients). Table 1 shows the overall characteristics of the patient population. The mean age was 61 ± 13 years, ranging from 19 to 85 years. The average heart rate was 68 ± 14 bpm. The mean effective dose of the whole examination was 2.4 ± 1.4 mSv, in the range of 0.6 to 9.8 mSv. The mean effective dose of CTCA alone was 1.5 ± 1.1 mSv, ranging from 0.4 to 7.4 mSv.

Descriptive characteristics of Group 1 and Group 2 are shown in Table 1. There were no significant differences in the study groups with gender, age, weight, and calcium scores. There was a significant difference in heart rate, with Group 1 averaging 59 ± 7 bpm and 80 ± 12 bpm for Group 2.

3.2. Radiation dose

The mean effective dose of CTCA in the entire patient population was 1.5 ± 1.1 mSv, of which 151 (43%) had an effective dose of <1 mSv. The mean effective dose of CTCA in Group 1 (1.2 ± 0.8 mSv) was lower than in Group 2 (1.9 ± 1.2 mSv), with a significant difference ($P < .001$). An effective dose of <1 mSv was recorded in 108 (55%) cases of Group 1, respectively, in 43 (28%) cases of Group 2. The radiation dose depending on heartbeat regularity is shown in Table 2. In patients with regular heart rhythm, we observed significantly lower radiation dose than in patients with irregular heart rhythm. The relation of DLP to patient weight for CTCA is shown in Figure 1.

3.3. Image quality

The image quality of the whole group of patients is shown in Table 3. Nondiagnostic examination was recorded in 8 cases

Table 1

Basic characteristics of all patients, Group 1 and Group 2.

	Total	Group 1	Group 2	*P* value
No. of patients	349	195	154	
Men/women	201/148	115/80	86/68	.558
Age (yr)	61 ± 13 (19–85)	61 ± 13	62 ± 11	.217
Weight (kg)	83 ± 16 (49–150)	82 ± 16	85 ± 16	.189
Heart rate (bpm)	68 ± 14 (41–131)	59 ± 7	80 ± 12	<.001
Calcium score	551 ± 1206 (0–10,521)	486 ± 1238	630 ± 1166	.277
Tube potential (kV)	108 ± 11 (100–120)	106 ± 10	109 ± 11	.038
Tube current (mA)	349 ± 129 (188–729)	330 ± 127	374 ± 127	.002
Radiation exposure of the whole examination (DLP; —mGy·cm)	174 ± 98 (46–698)	145 ± 75	211 ± 110	<.001
Radiation exposure of CTCA (DLP; —mGy·cm)	106 ± 76 (26–526)	84 ± 56	134 ± 88	<.001
Effective dose of examination in total (mSv)	2.4 ± 1.4 (0.6–9.8)	2 ± 1.1	3 ± 1.5	<.001
Effective dose of CTCA (mSv)	1.5 ± 1.1 (0.4–7.4)	1.2 ± 0.8	1.9 ± 1.2	<.001

Data in Total are expressed as mean ± standard deviation and range. Data in Group 1 and Group 2 are expressed as mean ± standard deviation.
CTCA = computed tomography coronary angiography, DLP = dose–length product.

Table 2

Radiation dose of CTCA in patient groups with regular and irregular heart rhythm.

Heart rhythm	No. of patients	DLP	mSv	*P* value
Regular	299	91 ± 56	1.3 ± 0.8	<.001
Irregular	50	197 ± 112	2.8 ± 1.6	

CTCA = computed tomography coronary angiography, DLP = dose–length product.

(2.3% of the total number of examinations) in 64.2% of cases, good to excellent quality examinations were observed (Likert scores 4 and 5), with an average Likert score of 3.8.

In Group 1, we reported good to excellent image quality in 76% of cases (Likert scores 4 and 5) and below-average quality (Likert scores 1 and 2) in 4% of cases, of which only 1% examinations from Group 1 were classified as nonevaluable. In Group 2, the incidence of good to excellent image quality was in 49% of cases and the incidence of below-average quality in 20% of cases, of which 4% were nonevaluable examinations (Fig. 2). The mean Likert score of Group 1 was significantly higher than in Group 2 (4.1 vs 3.4; $P < .001$). At the same time, there was no significant difference in the visual quality of examinations of patients with heart rates of >80 bpm compared to patients with heart rate within 71 to 80 bpm (mean Likert score 3.3 vs 3.4; $P = .531$).

Significant difference in image quality was noted when comparing patients with regular and irregular heart rhythm (Likert score 3.9 vs 3.3; $P = .012$; Table 4). Subsequently, we compared the image quality in patients with a high regular heart rate of >70 bpm to patients with an irregular heart rhythm. Between the 2 groups, we did not find a significant difference in image quality; the average Likert score was 3.4 to 3.3 ($P = .888$; Table 4).

4. Discussion

Patients with high heart rate, irregular heartbeat, atrial fibrillation, and high calcium score present a significant challenge in cardiac CT examinations.[18,19] To enhance the image quality and diagnostic accuracy of CTCA in such patients, several technologies have been developed, such as dual-source systems, large pitch factor scanning, and 320-layer detector systems.[20] These CT scanners were able to display coronary vessels with high image quality also to patients with heart rate of >65 bpm, which was previously considered a threshold value and when it exceeded, there was a significant deterioration of image quality while significantly increased radiation dose.[21,22] However, most studies investigating the effect of high heart rate on image quality included patients with only a slightly increased heart rate ranging from 65 to 80 bpm.[14,15]

In our prospective study, we demonstrated sufficient image quality and low radiation exposure even at high or irregular

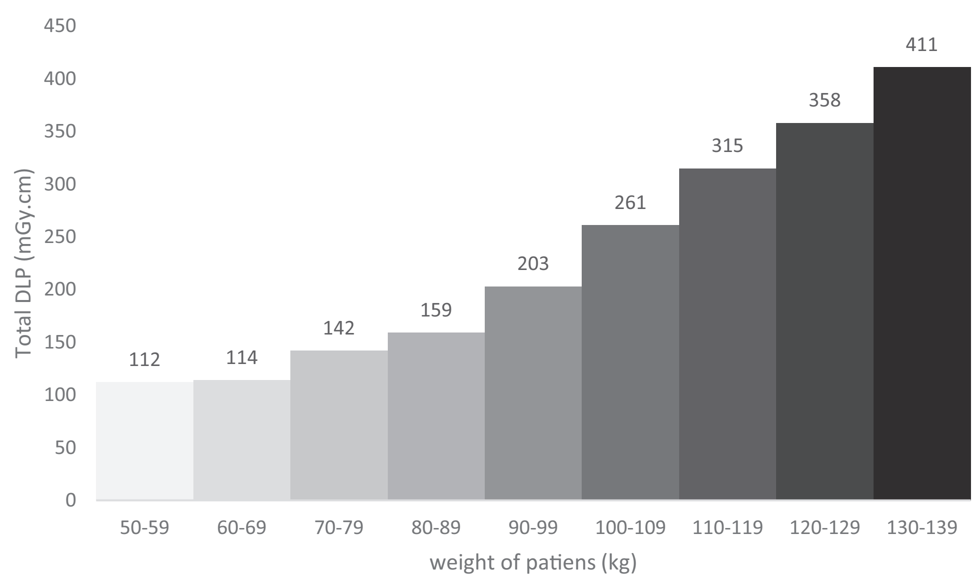

Figure 1. Relation of DLP on patient weight for CTCA. CTCA = computed tomography coronary angiography, DLP = dose–length product.

heart rates. In the group of patients with a regular heart rate of ≤70 bpm, we observed significantly better visual quality of the examination than in the group of patients with a heart rate >70 bpm or irregular heartbeat (Likert 4.1 vs 3.4, $P < .001$), respectively, the number of nonevaluable examinations was 1% vs 4%. There was a significant difference in mean effective dose of CTCA between the study groups (1.2 ± 0.8 vs 1.9 ± 1.2 mSv, $P < .001$). The difference in radiation exposure is due to the extension of the acquisition window (30%–50% + 70%–80% R-R interval) when scanning patients with high or irregular heart rate. Our data confirm that in a group of patients with a regular heart rate of up to 70 beats per minute, a short acquisition window of the 70% to 80% R-R interval is sufficient. In this group of patients, we achieved very low effective dose of CTCA below 1 mSv in more than half of the cases. When comparing the visual quality of the examination in the group of patients with regular heartbeat and patients with irregular heart rhythm, we calculated a significantly different Likert score (3.9 vs 3.3; $P = .012$), there was also a significant difference in the average effective dose (1.3 ± 0.8 vs 2.8 ± 1.6 mSv; $P < .001$). At the same time, there was no significant difference in the visual quality of examination of patients with a heart rate of >80 bpm compared to patients with a heart rate of 71 to 80 bpm (mean Likert score 3.3 vs 3.4; $P = .531$).

In the literature, we have found several studies investigating the influence of heart rate on the image quality and radiation exposure of CTCA, which were performed on 256-detector row CT scanner.[11,13,16] These studies have shown high diagnostic accuracy of 16-cm wide detector CT scanner at high heart rate or atrial fibrillation, comparing to invasive coronary angiography. Andreini et al[13] found in a group of patients with a heart rate of >80 bpm comparable image quality of CTCA to patients with a heart rate of <65 bpm. The same authors found no significant difference in the visual quality of the examination when comparing patients with atrial fibrillation and patients with sinus rhythm.[11] Differing results from our study may have been due to a different CT protocol, Andreini et al use a wider acquisition window in the range of 40% to 80% of the R-R interval in case of high or irregular heart rhythm with median image quality score 3 in the whole population and similar score between groups.[11,13] In another similar study using 16-cm wide detector system, Latif et al[23] retrospectively analyzed 439 patients with different heart rates, their results showed significantly different image quality between patients with heart rate of ≤70 bpm (overall Likert scale 4.2), and patients with heart rate of >70 bpm (Liker scale 3.8). In contrast to our study, Latif et al[23] observed no difference in effective radiation dose between low and high heart rate study groups; the mean effective dose was 4.2 and 4.3 mSv, respectively.

The mean effective dose values in groups of patients with high or irregular heart rate from our study are similar to those reported in the literature (1.9 ± 1 to 3.9 ± 2.1 mSv, using the 16-cm CT scanner).[11–13,16,17] Low effective dose (1.9 ± 0.3 mSv) and very good image quality were achieved with a 128-slice dual-source CT scanner at a heart rate of 76 to 80 bpm.[15] The high image quality of dual-source CT has also been demonstrated at heart rates of >80 bpm, but at the cost of very high radiation exposure (21.5 ± 4.3 mSv).[24] A meta-analysis examining the radiation load of CTCA in atrial fibrillation reports average effective doses ranging from 9 to 16 mSv.[25] Also, our results affirm the relationship between DLP in CTCA and patient weight, that is, the higher the patient weight, the higher the DLP.

Table 3

Image quality of the entire group of patients.

Image quality	Insufficient Likert = 1	Below-average Likert = 2	Average Likert = 3	Good Likert = 4	Excellent Likert = 5	Mean Likert score
No. of cases	8	31	86	126	98	3.8
% of Cases	2.3%	8.9%	24.6%	36.1%	28.1%	

5. Study limitations

We acknowledge certain limitations to our study. First, this is a single-center study of nonrandomized patient population. Second, manually triggering a CTCA scan based upon no contrast seen in the right ventricle could be a major contributor to contrast opacification of coronaries and may affect overall image quality. Third, the impossibility of comparing CTCA results with invasive coronary angiography was another limitation of our study; however, this was not the aim of our study. Fourth, the estimation of the effective dose from DLP

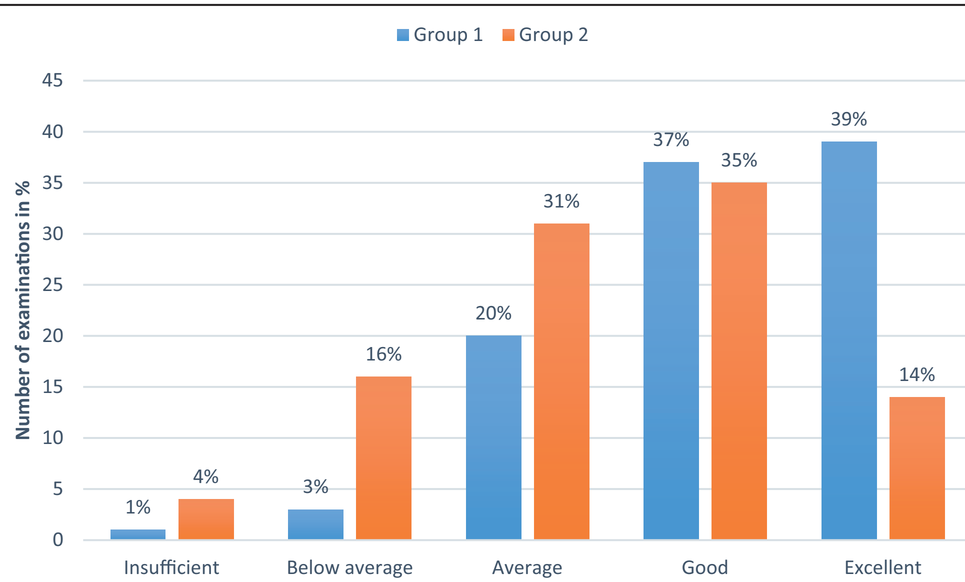

Figure 2. Image quality comparison between Group 1 and Group 2.

Table 4

Comparison of image quality between groups of patients with regular and irregular heart rhythm.

Heartbeat	No. of cases	Insufficient Likert = 1	Below-average Likert = 2	Average Likert = 3	Good Likert = 4	Excellent Likert = 5
Regular ≤70 bpm	195	2 (1%)	6 (3%)	39 (20%)	72 (37%)	76 (39%)
Regular >70 bpm	104	3 (3%)	17 (16%)	32 (31%)	36 (35%)	16 (15%)
Irregular	50	3 (6%)	8 (16%)	15 (30%)	18 (36%)	6 (12%)

is less accurate than the calculation using Monte Carlo simulation for individual patient, as patient size deviates from the average size.

6. Conclusion

In our single-center prospective study, we have shown that a CT scanner with 16-cm wide detector enables low radiation exposure during CTCA even at high or irregular heart rates. Good CTCA image quality and low dose are related to low heart rate.

Author contributions

Conceptualization: MO, AK.
Data curation: MO, DS, DC, AK
Formal analysis: MO, DS, DC, AK.
Investigation: MO.
Writing—original draft: MO, AK.
Writing—review & editing: MO, DS, DC, AK.

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