European Journal of Radiology 81 (2012) 2221–2230

Contents lists available at SciVerse ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Impact of heart rate and rhythm on radiation exposure in prospectively ECG triggered computed tomography

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ARTICLE INFO

Article history:
Received 20 July 2011
Received in revised form
27 September 2011
Accepted 29 September 2011

Keywords:
CT
ECG
Radiation exposure
Prospective
Arrhythmia

ABSTRACT

Purpose: To evaluate the influence of different heart rates and arrhythmias on scanner performance, image acquisition and applied radiation exposure in prospectively ECG triggered computed tomography (pCT).
Materials and methods: An ECG simulator (EKG Phantom 320, Müller & Sebastiani Elektronik GmbH, Munich, Germany) was used to generate different heart rhythms and arrhythmias: sinus rhythm (SR) at 45, 60, 75, 90 and 120/min, supraventricular arrhythmias (e.g. sinus arrhythmia, atrial fibrillation) and ventricular arrhythmias (e.g. ventricular extrasystoles), pacemaker-ECGs, ST-changes and technical artifacts.

The analysis of the image acquisition process was performed on a 64-row multidetector CT (Brilliance, Philips Medical Systems, Cleveland, USA). A prospectively triggered scan protocol as used for routine was applied (120 kV; 150 mA s; 0.4 s rotation and exposure time per scan; image acquisition predominantly in end-diastole at 75% R-R-interval, in arrythmias with a mean heart rate above 80/min in systole at 45% of the R-R-interval; FOV 25 cm). The mean dose length product (DLP) and its percentage increase from baseline (SR at 60/min) were determined.
Result: Radiation exposure can increase significantly when the heart rhythm deviates from sinus rhythm. ECG-changes leading to a significant DLP increase ($p < 0.05$) were bifocal pacemaker (61%), pacemaker dysfunction (22%), SVES (20%), ventricular salvo (20%), and atrial fibrillation (14%). Significantly ($p < 0.05$) prolonged scan time (>8 s) could be observed in bifocal pacemaker (12.8 s), pacemaker dysfunction (10.7 s), atrial fibrillation (10.3 s) and sinus arrhythmia (9.3 s).
Conclusion: In prospectively ECG triggered CT, heart rate and rhythm can provoke different types of scanner performance, which can significantly alter radiation exposure and scan time. These results might have an important implication for indication, informed consent and contrast agent injection protocols.

1. Introduction

To reduce radiation exposure in cardiac CT, modern scanners allow a prospectively ECG triggered sequential image acquisition (pCT). This techniques reduces the radiation exposure by 77–83% compared to a retrospectively gated acquisition mode (rCT) without ECG-modulation of the tube current and by 50% with ECG modulation [1–4]. With the prospectively ECG triggered acquisition mode, the so-called step-and-shoot technique, usually 4 incremental scan steps are sufficient in order to cover the whole heart in a 64 row CT. The scan steps are performed with a slight overlap whereas in patients with heart rates below 75/min every second QRS complex is skipped. In previously published studies on pCT only patients with sinus rhythm, atrial fibrillation and low heart rate were included [5–7]. Patients with other ECG alterations were either excluded a priori or examined by rCT [8,9]. Therefore the impact of ECG changes on the applied radiation exposure and scanner performance in pCT is widely unknown.

The purpose of the study was to analyze the impact of different ECG alterations generated by an ECG simulator on the image acquisition process in pCT regarding radiation exposure, scan time, scan abortion and number of repeated scans.

2. Materials and methods

2.1. ECG simulator

The ECG simulator used (EKG Phantom 320, Müller & Sebastiani Elektronik GmbH, Munich, Germany) has 12 leads in total: six limb

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doi:10.1016/j.ejrad.2011.09.019

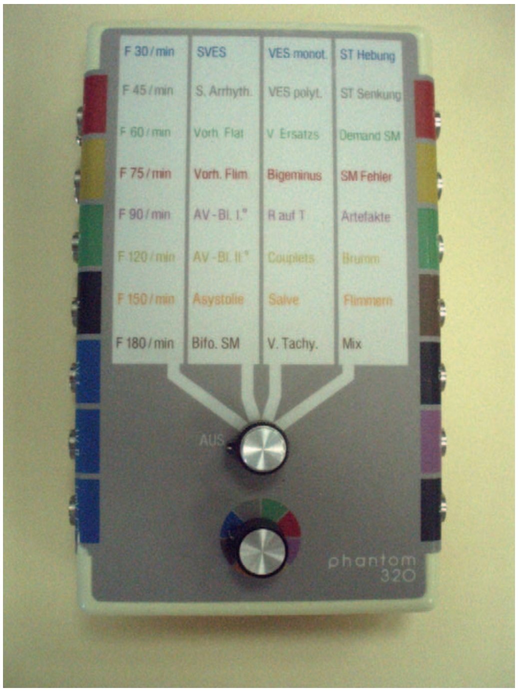

Fig. 1. ECG-simulator ("EKG-Phantom 320", Müller & Sebastiani Elektronik GmbH, Munich, Germany).

leads (I–III, avR, avL, avF) and six precordial leads (V1–V6) which can be picked off by 4 mm banana jacks or button electrodes (Fig. 1). In total 32 different ECG changes can be simulated including 8 sinus rhythms with heart rates 30–180/min, 7 supraventricular arrhythmias, 9 ventricular arrhythmias, ST-changes as well as technical artifacts.

For the ECG simulation the limb leads (I–III) were picked off by common ECG cables. The adjustment of the different ECG changes was performed manually. The ECG signal was depicted by an external ECG monitor and by the control console of the scanner. The maximum altitude of the signal was: lead I: +1.35–1.49 mV, lead II: +2.35–2.49 mV, lead III: +0.95–1.06 mV. As no cardiac CT would be carried out in patients with VT, VF, a SR at 30, 150 or 180/min, these ECG changes have been neglected in the study.

2.2. Scan protocol

The analysis of the image acquisition process was performed on a 64 row CT (Brilliance 64, Philips Medical Systems, Cleveland, OH, USA). The parameters of the scanning protocol, which is used in our institution in daily routine for cardiac pCT, are listed in Table 1. For image acquisition in heart rates below 80/min, the end-diastole at 75% of the R-R-interval was used, since this usually corresponds to the heart phase with the lowest motion artifacts. For image acquisition at a mean heart rate above 80/min the systole at 45% of the R-R- interval was performed. In the case that an arrhythmia would change the heart rate accidently above 80/min the 75% and the 45% was performed and analyzed. The exposition time per scan was 0.4 s (360° scan angle). Thereof about 2/3 are used for image reconstruction, the remaining 1/3 ('padding') is used for corrections in case of variations of the heart rate during the examination.

The entire image acquisition process was defined as follows: a scan series consisted of several scan steps, each scan step consisted of a phase of image acquisition followed by a table feed. The number of image acquisition phases during a scan step could increase when the image acquisition failed due to ECG abnormalities and the image acquisition phase had to be repeated.

Table 1
Scan protocol parameters.

Parameter	Value
Tube current (kV)	120
Rotation time (s)	0.4
Exposure time per scan (s)	0.4
mAs product (electric)	150
mAs product (effective)	192
Collimation (mm)	64×0.625
Table feed (mm)	31.2
Pitch factor	0.78
Number of scan steps	6
Imaged scan length (mm)	187.2
CTDI vol (mGy)	11.3
DLP (mGy × cm)	211

To cover the entire heart, 4 steps are needed at a 64 row CT scanner with a detector width of 4 cm. Due to the cone beam effect, using a field-of-view (FOV) of 25 cm, the area of complete data acquisition is reduced down to 31.2 mm. Therefore the table feed during a single scan step is 31.2 mm. With four scan steps a range of 124.8 mm is covered in total. In the present study a scan range of 187.2 mm was chosen, corresponding to a series of six scan steps, to ensure a sufficient high probability for a coincidence of simulated, partially temporary ECG abnormalities during the acquisition. In irregular appearing ECG changes like SVES or asystole, the scan series were repeated until the corresponding ECG abnormality occurred at least during one image acquisition within three evaluable scan series. The number of image acquisitions in a scan series can add up to more than six due to scan abortions and repetition. The number of acquired scan series was adapted to the frequency of occurrence of certain ECG changes.

The simulated arrhythmias were based on a heart rate of 75/min. Therefore a possible increase in scan time was calculated in relation to a sinus rhythm with 75/min rather than 60/min despite the fact that the recommended maximum HR for incremental CT is 65/min.

The dose–length product (DLP) and the volume CT dose index ($CTDI_{vol}$) were documented for each scan series. The DLP increase was than calculated in relation to a standard routine scan series with 4 scan steps at a HR of 60/min. A single locater scan was performed for all scan series without being added to the DLP.

2.3. ECG alterations

The following ECG variants were used in the scanning protocol: sinus rhythm with different heart rates (45, 60, 75, 90 and 120/min), supraventricular extrasystoles (SVES), sinus arrhythmia, atrial flutter, atrial fibrillation, AV block I° and II°, intermittent asystole (>2.5 s), mono- and polytope ventricular extrasystoles (VES), ventricular compensatory rhythm, bigeminus, R-on-T phenomenon, couplets, ventricular salvo, ST elevations and ST depression, bifocal pacemaker, demand pacemaker, pacemaker dysfunction, technical artifacts, as well as a technical hum at 50 Hz.

3. Results

In total 109 scan series were performed under simulation of 26 different ECG abnormalities, including 83 repeated scan series. 15 scan series were performed with image acquisition within the systole at 45% of the R-R-interval in ECG alterations with a mean HR