Do Segmented Reconstruction Algorithms for Cardiac Multi-Slice Computed Tomography Improve Image Quality?

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Purpose: To evaluate segmented reconstruction algorithms for spiral multi-slice computed tomography (MSCT) that use data from two cardiac cycles to improve temporal resolution (τ) for imaging of the heart.

Materials and Methods: An initial group of 78 cardiac patients (heart rates [HR] = 63–167 beats per minute [bpm]) were imaged on a 4-slice, 500 ms gantry rotation time scanner (scanner 1). Images were reconstructed with a single-segment algorithm using data from one cardiac cycle with a reconstruction window of fixed length (τ = 250 ms). Images were also reconstructed with two variants of a multi-segment algorithm using data from two cardiac cycles where only one end of the reconstruction window was fixed and the other end was freely moveable to allow adjustment of τ according to HR: (1) "2-segment fixed start" with fixed start of reconstruction, (2) "2-segment fixed end" with fixed end of reconstruction (for both, τ = 125–250 ms). The resulting image sets were ranked from best to worst (1–3, respectively) in a side-by-side, blinded comparison by two independent readers. A second group of 26 patients (HR = 74–90 bpm) were imaged on a 12-slice, 420 ms gantry rotation time scanner (scanner 2). Data were reconstructed with a single-segment algorithm (τ = 210 ms) and a "2-segment fixed start" algorithm (τ = 105–210 ms) and image sets were ranked from best to worst (1–2, respectively).

Results: There was no clear evidence that any one technique is superior for imaging on scanner 1. Reader 1 ranked single-segment images the highest for all HRs, but statistically significant differences among the three algorithms were only found for the lowest HRs (< 80 bpm), where reader 1 preferred single-segment over "2-segment fixed end" techniques (p = 0.048). The highest rankings given by reader 2 varied according to HR: single-segment images were superior for lowest HRs, while "2-segment fixed start" images were superior for HRs > 80 bpm; none of these comparisons reached statistical significance. Improved performance of 2-segment reconstruction was found with scanner 2. Both readers ranked "2-segment fixed start" images the highest (p < 0.01).

Conclusions: The added value of 2-segment cardiac reconstruction algorithms for spiral MSCT was not demonstrated for a 4-slice, 500 ms gantry rotation time scanner but shown to be beneficial for a 12-slice, 420 ms gantry rotation time scanner in the crucial HR range of 74–90 bpm.

Key Words Computed tomography · Spiral · Image reconstruction · Temporal resolution · Heart

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Verbessern segmentierte Rekonstruktionsalgorithmen die Bildqualität bei kardiovaskulären Mehrschicht-Computertomographie-(MSCT-)Untersuchungen?

Hintergrund und Ziel: Die im Vergleich zu Elektronenstrahl-Computertomographie, Magnetresonanztomographie, Fluoroskopie und Ultraschall relativ geringe zeitliche Auflösung (τ) und entsprechend längere Bildakquisitionszeit gegenwärtiger Mehrschicht-Computertomographie-(MSCT-)Systeme sind ein wichtiger limitierender Faktor für kardiovaskuläre Untersuchungen. Mehrere spezielle Rekonstruktionsalgorithmen wurden mit dem Ziel entwickelt, die zeitliche Auflösung (τ) für kardiovaskuläre MSCT-Untersuchungen zu verbessern. Bei Einzelsegment-Rekonstruktionsalgorithmen stammt die

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gesamte Bildinformation jedes Schnittbildes aus einem einzelnen Herzzyklus, und die zeitliche Auflösung (τ) entspricht der Gantry-Rotationszeit (t_{rot})/2. Mehrsegment-Rekonstruktionsalgorithmen werden für Patienten mit hoher Herzfrequenz (HR) empfohlen (HR > 65–70 Schläge/min, abhängig vom benutzten System und Algorithmus), um die effektive zeitliche Auflösung im Vergleich zu Einzelsegmentalgorithmen zu erhöhen. Mehrsegmentalgorithmen reduzieren das Aufnahmezeitintervall, das durch Nutzung der Bildinformation aus derselben Phase von n aufeinander folgenden Herzzyklen zu jedem Schnittbild beiträgt. Mehrsegmentrekonstruktion erreicht eine zeitliche Auflösung zwischen t_{rot}/2n und t_{rot}/2, abhängig von der Herzfrequenz (Abbildungen 1 und 2). Das Ziel dieser Studie war zu untersuchen, ob Mehrsegment-Rekonstruktionsalgorithmen die Bildqualität tatsächlich verbessern. Die Bildqualität von 4- und 12-Schicht-Systemen wurde in Einzel- und Mehrsegmentrekonstruktionen mit n = 2 Herzzyklen verglichen.

Material und Methodik: Eine Gruppe von 78 Patienten (HR = 63–167 Schläge/min) wurde mit einem 4-Schicht-System mit 500 ms Gantry-Rotationszeit (SOMATOM Sensation 4, Siemens Medical Solutions, Erlangen; Scanner 1) untersucht. Die Untersuchungen wurden nach Kontrastmittelgabe in retrospektiv EKG-getriggerter Spiraltechnik durchgeführt. Die Bildrekonstruktion erfolgte mit einem Einzelsegmentalgorithmus der Bildinformation aus einem einzelnen Herzzyklus mit einem Rekonstruktionsfenster konstanter Länge (τ = 250 ms; Abbildung 3a). Darüber hinaus wurde die Bildrekonstruktion mit zwei verschiedenen Mehrsegmentalgorithmen durchgeführt. Diese Mehrsegmentalgorithmen nutzten die Bildinformation aus zwei Herzzyklen, wobei ein Ende des Rekonstruktionsfenster fixiert war und das andere Ende verschoben werden konnte mit dem Ziel, die zeitliche Auflösung (τ) der jeweiligen Herzfrequenz anzupassen. Die beiden Varianten wurden beschrieben als 1. „2-segment fixed start" mit festgelegtem Ausgangspunkt der Rekonstruktion (Abbildung 3b) und 2. „2-segment fixed end" mit festgelegtem Endpunkt der Rekonstruktion (für beide Varianten: τ = 125–250 ms; Abbildung 3c). Die Bildqualität der entsprechenden Bildsätze wurde auf einer Skala von 1 (höchste Qualität) bis 3 (niedrigste Qualität) mit einem „side-by-side" verblindeten Vergleich von zwei Untersuchern bewertet. Eine zweite Gruppe von Patienten mit Herzfrequenzen zwischen 74 und 90 Schlägen/min wurde mit einen 12-Schicht-System mit 420 ms Gantry-Rotationszeit (SOMATOM Sensation 16, Siemens Medical Solutions, Erlangen; Scanner 2) untersucht. Die Untersuchungen wurden nach Kontrastmittelgabe in retrospektiv EKG-getriggerter Spiraltechnik durchgeführt. Die Bildrekonstruktion erfolgte mit einem Einzelsegmentalgorithmus (τ = 210 ms) und einem „2-segment fixed start"-Algorithmus (τ = 105–210 ms). Die Bildqualität der entsprechenden Bildsätze wurde auf einer Skala von 1 (höchste Qualität) bis 2 (niedrigste Qualität) von zwei Untersuchern gewertet.

Ergebnisse: Die Mittelwerte („mean rank") der Bildqualität für die drei Bildsätze der mit Scanner 1 untersuchten Patienten sind in Tabelle 1 für zwei Untersucher zusammengefasst. Die Mittelwerte („mean rank") der Bildqualität für die drei Bildsätze in Abhängigkeit von der Herzfrequenz zeigt Tabelle 2. Die Bewertung der verschiedenen Rekonstruktionstechniken mit Scanner 1 war untersucherabhängig (Abbildung 4). Untersucher 1 bewertete die Bildqualität der Einzelsegmentrekonstruktion für alle Herzfrequenzen höher, signifikante Unterschiede zwischen den drei Rekonstruktionsalgorithmen wurden jedoch nur für niedrige Herzfrequenzen (HR < 80 Schläge/min) gefunden. Für diese Herzfrequenzen bewertete Untersucher 1 Einzelsegment- höher als „2-segment fixed end"-Techniken (p = 0,048). Die Bewertung der Bildqualität durch Untersucher 2 hing von der Herzfrequenz ab: Die Bildqualität von Einzelsegmentrekonstruktionen war für niedrigere Herzfrequenzen höher, während die Bildqualität von „2-segment fixed start"-Rekonstruktionen für Herzfrequenzen > 80 Schläge/min höher bewertet wurde. Allerdings erreichten diese Unterschiede für Untersucher 2 in keinem der Vergleiche statistische Signifikanz. Insgesamt zeigten die Ergebnisse der mit dem 4-Schicht-System untersuchten Patienten, dass Einzelsegmentalgorithmen für Herzfrequenzen zwischen 63 and 80 Schlägen/min bevorzugt wurden und dass die "2-segment fixed end"-Algorithmen für alle Herzfrequenzen keinen Vorteil aufwiesen. Allerdings erreichten die Unterschiede zwischen den verschiedenen Rekonstruktionstechniken mit Scanner 1 keine statistische Signifikanz. Die Mittelwerte („mean rank") der Bildqualität für die Bildsätze der mit Scanner 2 untersuchten Patienten sind in Tabelle 3 für zwei Untersucher zusammengefasst. 2-Segment-Rekonstruktionen hatten bei Untersuchungen mit dem 12-Schicht-System einen größeren Einfluss (Abbildung 5). Beide Untersucher bewerteten die Bildqualität mit „2-segment fixed start"-Rekonstruktionen höher (p < 0,01).

Schlussfolgerung: Beim Einsatz von 4-Schicht-MSCT-Systemen mit 500 ms Gantry-Rotationszeit führte die höhere effektive zeitliche Auflösung (τ) mit 2-Segment-Rekonstruktion kardiovaskulärer Untersuchungen nicht zu einer verbesserten Bildqualität (Abbildung 6). Im Gegensatz dazu konnten bei Verwendung von „state-of-the-art" 12-Schicht-Systemen mit 420 ms Gantry-Rotationszeit Verbesserungen der Bildqualität mit 2-Segment-Rekonstruktion im Vergleich zu Einzelsegmentrekonstruktion für Herzfrequenzen zwischen 74 und 90 Schlägen/min erreicht werden.

Schlüsselwörter: Computertomographie · Spirale Aufnahme · Bildrekonstruktion · Zeitliche Auflösung · Herz

Introduction

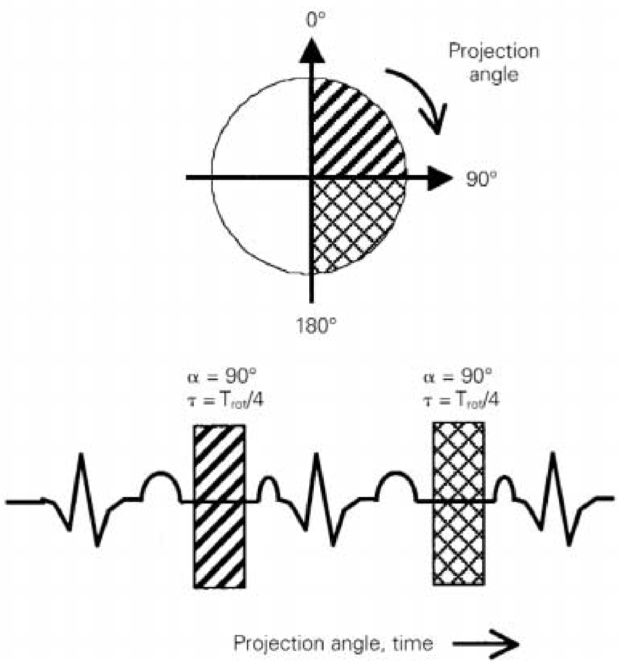
Mechanical multi-slice computed tomography (MSCT) scanners capable of the simultaneous acquisition of multiple slices, subsecond gantry rotation times (t_{rot}), and synchronization of data to the cardiac cycle have recently been introduced for imaging of the heart [5, 6, 11]. These systems provide the high spatial resolution and fast volume coverage essential for the evaluation of cardiovascular disease. However, the major limitation of current MSCT technology for cardiac applications is a relatively long temporal resolution (acquisition time per image) [13] compared to other techniques such as electron beam CT, magnetic resonance imaging, fluoroscopy, and ultrasound.

Several dedicated reconstruction algorithms have been developed to optimize temporal resolution for cardiac imaging with spiral MSCT [2, 3, 7, 9, 10, 15, 16]. Most approaches acquire data continuously with simultaneous recording of the ECG signal and reconstruct data during retrospectively selected heart phases. Single-segment reconstruction algorithms obtain all the projection data for each image from a single cardiac cycle and achieve temporal resolutions equal to approximately $t_{rot}/2$ [9, 10, 15]. Implementations of single-segment algorithms by the different CT manufacturers have various names including "single-phase" and "single-sector" reconstruction. Multi-segment reconstruction algorithms have been proposed for patients with higher heart rates (HRs) (HRs > 65–70 beats per minute [bpm]) depending on the scanner and the specific algorithm) to increase the effective temporal resolution beyond that obtained with single-segment algorithms for cardiac images [2, 3, 5, 10]. Multi-segment algorithms obtain the data for each image from the same heart phase of n consecutive cardiac cycles and achieve a maximum temporal resolution of $t_{rot}/2n$. The different CT manufacturers have implemented segmented reconstruction algorithms under names such as "multi-phasic", "multi-sector", "snapshot burst" and "adaptive cardio volume" reconstruction.

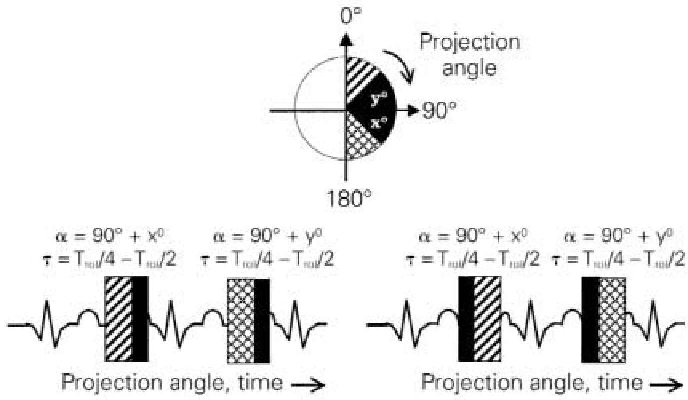
Both single-segment and multi-segment algorithms utilize modified partial-scan reconstruction techniques. Partial-scan reconstruction requires only 180° + δ (δ < fan angle) of fan-beam projection data to create an image at a given reconstruction position. The fan-beam geometry of the acquired data is transformed to parallel-beam geometry using rebinning techniques. Transformation to parallel-beam geometry results in 180° of complete parallel projections as well as incomplete parallel projections containing redundant data. Omission of redundant data during reconstruction with single-segment algorithms yields a temporal resolution for each image equal to $t_{rot}/2$ for an object centered within the scan field.

With multi-segment algorithms, the time interval contributing to each image is effectively reduced by up to a factor of 1/n by dividing the partial-scan data set into n subsegments containing data from n cardiac cycles. The exact improvement in temporal resolution with multi-segment reconstruction, however, depends on the phase difference between the gantry rotation frequency and the patient's HR [5]. In order to achieve the best temporal resolution, this phase difference must permit acquisition of nonoverlapping, time-consistent data segments during consecutive gantry rotations to form a complete data set in parallel geometry. The partial-scan interval may then be divided into n equal-size subsegments where each subsegment spans a temporal interval of $t_{rot}/2n$ during the same relative heart phase of consecutive cardiac cycles (Figure 1a). When the phase difference is such that partially overlapping projection angles are acquired in consecutive cardiac cycles, the partial-scan interval is divided into n subsegments of different size which span temporal intervals between $t_{rot}/2n$ and $t_{rot}/2$ (Figure 1b). In this case, the temporal resolution of the image equals the temporal data interval of the largest subsegment. When the patient's HR and the gantry rotation frequency are completely synchronous, the same projection angle range is obtained during consecutive cardiac cycles and the entire partial-scan data set must effectively be obtained from a single cardiac cycle such that no improvement in temporal resolution is realized over single-segment reconstruction techniques ($t_{rot}/2$; Figure 1c). Therefore, multi-segment reconstruction algorithms can only achieve the optimal temporal resolution for certain combinations of HR and t_{rot} and all other combinations fail to reach the optimal value (Figure 2). Since HR typically varies during the examination, consistent achievement of the optimal temporal resolution would require dynamic adjustment of the gantry rotation speed. Because this is not technically feasible, t_{rot} is fixed during the scan and temporal resolution is defined dynamically as a function of the HR at each reconstruction position and ranges from $t_{rot}/2n$ to $t_{rot}/2$.

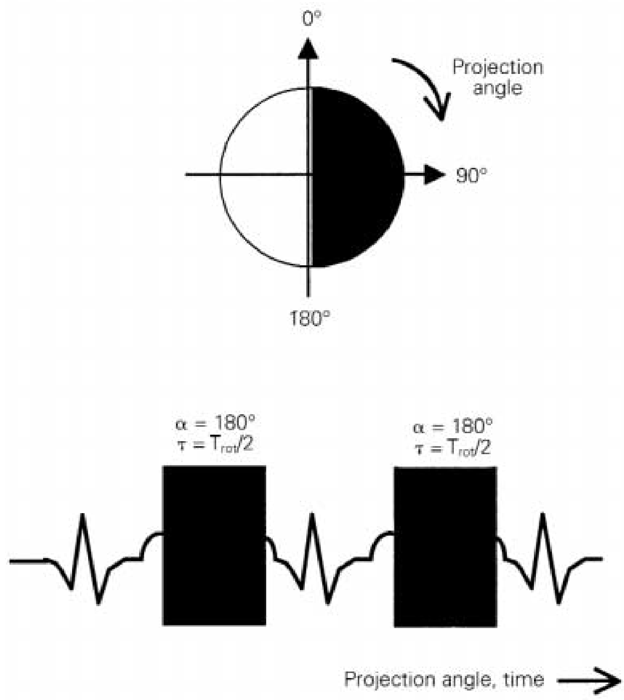
The best approach to dynamically adjusting the temporal resolution with respect to the cardiac cycle is unclear. As stated previously, correlation of data reconstruction to the cardiac cycle is accomplished by refer-



Figue 1a – Abbildung 1a



Figue 1b – Abbildung 1b



Figue 1c – Abbildung 1c

Figures 1a to 1c. Diagram of segmented reconstruction with n = 2 cardiac cycles. The circular graphs represent the partial-scan interval in parallel geometry. a) With an optimal phase difference between the frequency of the gantry rotation time and the patient's heart rate, a complete partial-scan data set is formed from two nonoverlapping subsegments reconstructed during the same cardiac phase of consecutive heart cycles with temporal resolutions equal to $t_{rot}/2n$. b) When partially overlapping projection angles are acquired, temporal resolution is determined by the largest subsegment of data and ranges from $t_{rot}/2n$ to $t_{rot}/2$. Either the ending or starting time of the reconstruction window is adjusted. c) When the phase difference is 0, completely overlapping projection angles are reconstructed and temporal resolution is equal to $t_{rot}/2$.

Abbildungen 1a bis 1c. Diagramm einer segmentierten Rekonstruktion mit n = 2 Herzzyklen. Die kreisförmigen Skizzen repräsentieren das Teilscan-Intervall in paralleler Geometrie. a) Bei optimaler Phasendifferenz zwischen der Frequenz der Gantry-Rotationszeit und der Herzfrequenz des Patienten entsteht ein kompletter Teilscan-Datensatz aus zwei nicht überlappenden Subsegmenten, die während derselben Phase aus aufeinander folgenden Herzzyklen mit einer zeitlichen Auflösung von $t_{rot}/2n$ rekonstruiert werden. b) Bei Aufnahme teilweise überlappender Projektionswinkel wird die zeitliche Auflösung vom größten Datensubsegment bestimmt und liegt zwischen $t_{rot}/2n$ und $t_{rot}/2$. Die End- oder Anfangszeit des Rekonstruktionsintervalls wird verändert. c) Ist die Phasendifferenz gleich 0, werden vollständig überlappende Projektionswinkel rekonstruiert, und die zeitliche Auflösung entspricht $t_{rot}/2$.

encing the patient's ECG signal. For morphologic imaging, data are ideally reconstructed during the portion of diastole indicated by a period of low electrical activity from just after the T-wave to the middle of the P-wave of the ECG signal. For higher HRs (> 60 bpm for t_{rot} = 500 ms; > 70 bpm for t_{rot} = 420 ms), data must often be reconstructed during periods of ventricular and/or atrial contraction with a single-segment temporal reconstruction window equal to $t_{rot}/2$. Placement of the reconstruction window should typically be the same for multi-segment reconstruction to allow for the longest possible temporal window, equal to $t_{rot}/2$. For combinations of t_{rot} and HR resulting in improved temporal resolution with multi-segment reconstruction ($t_{rot}/2n$–$t_{rot}/2$), the reconstruction window is shortened by adjusting either the ending or starting time (Figure 1b). With an adjustable starting time and a fixed ending time, any improvement in temporal resolution decreases the amount of data reconstructed

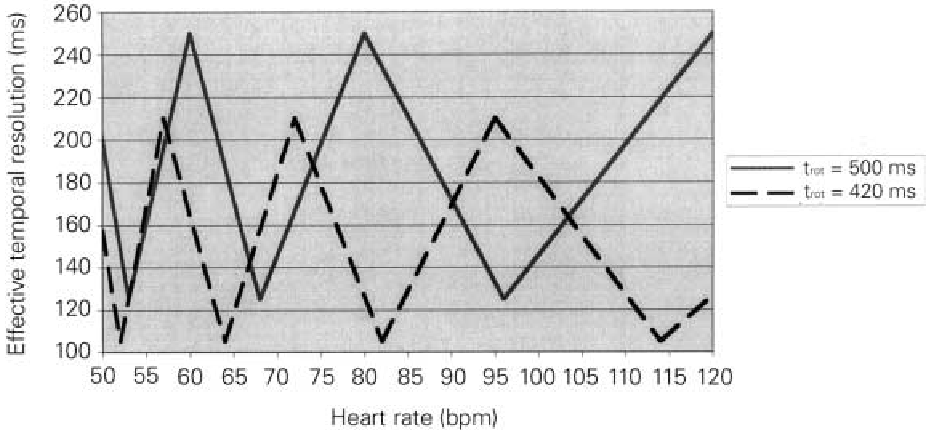


Figure 2. Effective temporal resolution achieved at clinically relevant heart rates (HRs) using segmented reconstruction with n = 2 cardiac cycles for a gantry rotation time (t_{rot}) of 500 ms (———) and 420 ms (– – – – –). Absolute minimum temporal resolution can only be achieved for certain combinations of HR and t_{rot}.

Abbildung 2. Bei klinisch relevanten Herzfrequenzen (HR) mit segmentierter Rekonstruktion, n = 2 Herzzyklen und einer Gantry-Rotationszeit (t_{rot}) von 500 ms (———) und 420 ms (– – – – –) erreichte effektive zeitliche Auflösung. Die absolute minimale zeitliche Auflösung lässt sich nur für bestimmte Kombinationen von HR und t_{rot} erreichen.

during the end of ventricular contraction and rapid filling, indicated by the T-wave. With an adjustable ending time and a fixed starting time, any improvement in temporal resolution decreases the amount of data reconstructed during contraction of the atria indicated by the P-wave. Although overall mechanical motion of the heart is greatest during ventricular contraction, some parts of the cardiac anatomy (specifically, the right coronary and left circumflex arteries positioned in the coronary groove) experience rapid motion during the end of ventricular diastole as a result of atrial contraction [1]. Therefore, specific timing of the dynamic temporal window used with multi-segment reconstruction could impact the usefulness of the algorithm.

The efficacy of multi-segment algorithms is also influenced by the number of subsegments defining the partial-scan data set. Specifically, the combination of data from consecutive heart cycles can degrade time sensitivity profiles (TSP) if any inconsistencies exist due to arrhythmia [3]; as the number of data subsegments increases, the probability of deviation from the desired cardiac phase and subsequent broadening of the TSP increases. In addition, data for a given reconstruction position must be acquired by at least one of the detectors during each heart cycle. Because the table is moving continuously, data points acquired from different heart cycles differ in spatial distance from the desired image position according to the table feed [5]. For multi-segment reconstruction from a large number of cardiac cycles, interpolation of data acquired at a long spatial distance from the desired position must be performed for standard table feeds which results in broadening of the slice sensitivity profile (SSP) and decreased longitudinal spatial resolution [2, 5]. Finally, reconstruction with subsegments from a large number of cardiac cycles would increase susceptibility to variations in contrast agent concentration over time that result from arterial bolus injection. For these reasons, only n = 2 is usually recommended for morphologic imaging which results in temporal resolutions of 125–250 ms with t_{rot} = 500 ms and 105–210 ms with t_{rot} = 420 ms.

Ohnesorge et al. described a single-segment reconstruction technique for retrospectively ECG-gated spiral data obtained with a 4-slice, 500 ms rotation time scanner which provided a temporal resolution equal to 250 ms [15]. Preliminary clinical evaluation of the algorithm for cardiac imaging demonstrated good overall image quality [15]. Flohr & Ohnesorge showed an improvement in image quality using multi-segment reconstruction with n = 2 compared to single-segment reconstruction on a 4-slice, 500 ms scanner in a small group of patients [5].

The purpose of the current study was to evaluate a larger patient group and determine if multi-segment reconstruction algorithms actually improve the quality of cardiac images in clinical practice. Image quality using single-segment and multi-segment reconstruction with n = 2 cardiac cycles was compared for a 4-slice, 500 ms gantry rotation time scanner (scanner 1) and a 12-slice, 420 ms gantry rotation time scanner (scanner 2).

Materials and Methods

Study Design

The study's sample size was based on the number of patients required for pairwise comparisons of three reconstruction algorithms at a significance level of (two-tailed) 0.0167 (i.e., 0.05/3). A sample size of 26 patients was found to have > 85% power to detect a reconstruction algorithm that was better than another 90% of the time [14]. The first goal was to evaluate the relative performance of each algorithm implemented on scanner 1. In order to assess the algorithms at different HRs, it was determined that 26 patients were needed in each of three HR categories: 63–80 bpm, 80–95 bpm, and > 95 bpm. A second goal was to compare the performance of two of the algorithms on a faster scanner, scanner 2, in a single HR range (74–90 bpm). This HR range was targeted because optimal performance of 2-segment reconstruction is predicted in this range for t_{rot} = 420 ms (Figure 2). This portion of the study required an additional 26 patients.

A total of 104 patients (61 male, 43 female; aged 11–80 years, mean = 54 years) were retrospectively selected for inclusion in the study with the approval of the Institutional Review Board. All patients received an MSCT examination as a part of their routine medical care. The patients in the study were referred for MSCT for suspicion of a variety of cardiovascular diseases including pulmonary vein stenosis (n = 50), cardiac mass (n = 11), aortic disease (n = 10), cardiac chamber disease (n = 9), coronary artery disease (n = 8), pericardial disease (n = 7), congenital heart disease (n = 7), valvular disease (n = 1), and chronic ischemic heart disease (n = 1).

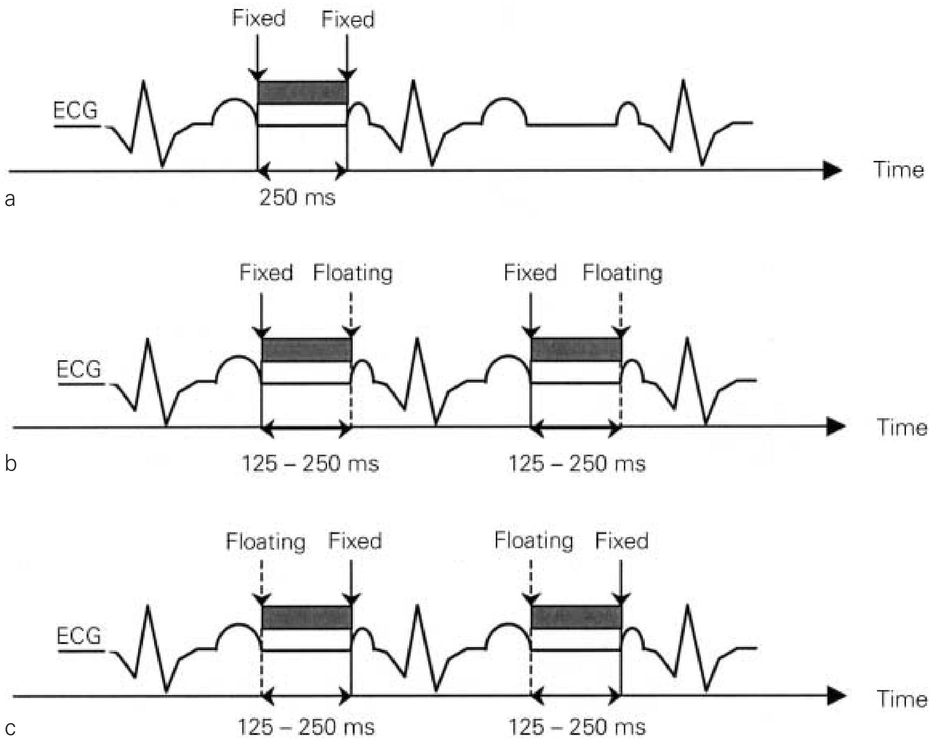
Image Acquisition

Scanner 1. The first group of 78 patients was imaged on a 4-slice, 500 ms gantry rotation time CT scanner (SOMATOM Sensation 4, Siemens Medical Solutions, Erlangen, Germany) or scanner 1 using contrast-enhanced retrospectively ECG-gated spiral techniques. Only patients with average HRs > 63 bpm were enrolled in this portion of the study because 2-segment reconstruction, as implemented on the Siemens Sensation 4, is not invoked below 63 bpm. For patients with varying HRs that dropped below 63 bpm during the scan, the algorithm immediately switched from 2-segment to 1-segment reconstruction. Contrast agent transit time was determined using a 20 ml timing bolus (Ultravist 300, Berlex, Wayne, NJ, USA) injected at a rate of 2.5 ml/s. The spiral scan was initiated with the appropriate delay after a typical injection of 100 ml of contrast agent at 2.5 ml/s. The scanning range was usually started just above the coronary arteries (slightly higher for assessment of pulmonary vein stenosis) and was extended to the most caudal portion of the heart. Data were acquired continuously with the simultaneous recording of the patient's digitized ECG signal. Acquisition parameters included slice collimation = 4 × 1 mm, tube current = 300 mA, and a tube voltage = 120 kV. Advancement of the patient table was varied according to the patient's HR; the table feed was 3 mm/s for patients with HRs recorded as < 80 bpm just prior to scanning and 3.6 mm/s for patients with HRs > 80 bpm. All scans were performed within a single inspiratory breathhold preceded by mild hyperventilation. The maximum effective patient radiation dose was approximately 10 mSv for females and 7 mSv for males (calculated using "WinDose", Scanditronix-Wellhoefer, Institute of Medical Physics, University Erlangen-Nuremberg, Germany).

The raw projection data and ECG signal from each scan were transferred to an off-line PC for reconstruction. The data were retrospectively gated to the ECG signal and images were reconstructed using three different algorithms (Cardiac Works-in-Progress Software, Siemens Medical Solutions, Erlangen, Germany): (1) single-segment algorithm where data are obtained during a single cardiac cycle using 250 ms reconstruction window with fixed start and end points (single-segment, Figure 3a) [15], (2) segmented algorithm where data are obtained during the same phase of two consecutive cardiac cycles using 125–250 ms reconstruction window with a fixed starting position and floating ending position ("2-segment fixed start", Figure 3b) [5], (3) segmented algorithm where data are again obtained during two cardiac cycles using 125–250 ms reconstruction window but with a floating starting position and a fixed ending position ("2-segment fixed end", Figure 3c). The position of the reconstruction window was defined with respect to R-peaks of the ECG signal and was equivalent for all three algorithms. Specifically, the fixed start and end points of the single-segment reconstruction window defined the fixed start of the "2-segment fixed start" window and the fixed end of the "2-segment fixed end" window, respectively (Figure 3). The 250 ms single-segment reconstruction window dictated relative placement of the other reconstruction windows. The fixed start of this window was defined as an absolute time before each R-peak and varied between 275–400 ms according to HR.

All images were reconstructed using a medium-sharp body kernel, B30f, with a spatial resolution of 12 line pairs per centimeter (cutoff). Overlapping images were reconstructed with an approximate slice width of 1.25 mm and an image increment of 0.5 mm.

Scanner 2. The second group of 26 patients was imaged on a state-of-the-art 12-slice, 420 ms rotation time scanner (SOMATOM Sensation 16, Siemens Medical Solutions, Erlangen, Germany), scanner 2, again using



Figures 3a to 3c. Schematic illustrates reconstruction techniques for retrospectively ECG-gated multi-slice spiral computed tomography (MSCT) implemented on scanner with 500 ms gantry rotation. Each technique requires 250 ms of data for the reconstruction of an image. a) Single-segment: reconstructs data from a single cardiac cycle. b) "2-segment fixed start": reconstructs data from two consecutive cardiac cycles; starting position of reconstruction window is fixed while ending position is floating in order to dynamically adapt to changing heart rate. c) "2-segment fixed end": reconstructs data from two consecutive cardiac cycles; ending position of reconstruction window is fixed while starting position is floating.

Abbildungen 3a bis 3c. Schematische Darstellung der Rekonstruktionstechniken für retrospektiv EKG-getriggerte Mehrschicht-Spiral-Computertomographie (MSCT) bei Verwendung eines Scannersystems mit 500 ms Gantry-Rotation. Jede Technik erfordert eine Datenakquisitionszeit von 250 ms zur Rekonstruktion eines Bildes. a) Einzelsegmentrekonstruktion: rekonstruiert Daten aus einen einzelnen Herzzyklus. b) „2-segment fixed start"-Rekonstruktion: rekonstruiert Daten aus zwei aufeinander folgenden Herzzyklen, die Ausgangsposition des Rekonstruktionsfenster ist festgelegt, die Endposition dagegen variabel, um eine dynamische Anpassung an die Herzfrequenz zu ermöglichen. c) „2-segment fixed end"-Rekonstruktion: rekonstruiert Daten aus zwei aufeinander folgenden Herzzyklen; die Endposition des Rekonstruktionsfensters ist festgelegt, die Anfangsposition dagegen variabel.

contrast-enhanced retrospectively ECG-gated spiral techniques. Data acquisition was similar to that described previously with the following exceptions. A primary bolus of ~ 100 ml of contrast agent was injected at a flow rate of 3.5 ml/s prior to the start of the scan. Changes in acquisition parameters in this case included t_{rot} = 420 ms, slice collimation = 12 × 0.75 mm, and tube current = 370 mA. A decrease in t_{rot} (from 500 to 420 ms) and an increase in the number of slices per rotation (from 4 to 12) permitted acquisition of data at a slower table feed, 2.8 mm/s, within a reasonable breathhold. The maximum effective patient radiation dose was comparable to techniques on scanner 1.

Spiral data were reconstructed using single-segment and "2-segment fixed start" techniques. The start of both reconstruction windows was defined as a relative time before each R-peak and varied between 50–60% according to HR.

Data Analysis

For each patient, the two or three sets of reconstructed images were evaluated independently by two experienced cardiac radiologists (RDW, AES) blinded to the reconstruction technique. Image sets were assessed for conspicuity of normal anatomy and the disease entity and ranked based on overall diagnostic value. The specific approach used was left to the reviewer.

Scanner 1. For the first group of patients imaged on scanner 1, the reconstructed images were ranked from best to worst (1–3, respectively); two or three image sets of equal quality were assigned the same ranking. Friedman's two-way nonparametric test was used to test the null hypothesis that the three reconstruction algorithms were equally preferred versus the alternative hypothesis that there was at least one difference in reader preference among the three algorithms. When this overall test was significant ($p < 0.05$), pairwise comparisons between algorithms were performed. To control the type I error rate for pairwise comparisons, reported p-values were adjusted for the number of pairwise comparisons [7].

Scanner 2. For the second group of patients imaged on scanner 2, image sets were similarly ranked as best or worst (1 or 2, respectively); image sets of equal quality were both assigned a ranking of 1. The Wilcoxon signed-rank test was used to test the null hypothesis that the two techniques are equally preferred versus the alternative hypothesis that there is a difference in reader preference between techniques. A significance level of 0.05 was applied.

Results

Scanner 1

Patients imaged on scanner 1 had average HRs of 73.0 ± 4.2 bpm, 86.9 ± 4.5 bpm, and 109.1 ± 15 bpm in each of the three HR categories. The mean rank of the three image sets for all patients in this group is summarized for each reader in Table 1. Preference for a given technique implemented on scanner 1 was reader-dependent (Figures 4a to 4c). Reader 1 ranked images reconstructed with the single-segment algorithm the highest (mean rank = 1.65), whereas reader 2 ranked "2-segment fixed start" images the highest (1.71); "2-segment fixed end" images were ranked the worst by both readers (2.13 and 2.01 by readers 1 and 2, respectively; Table 1). For readers Friedman's test indicates that the mean rankings were not the same (p = 0.006, Table 1). Pairwise comparisons of the rankings indicated that the single-segment algorithm was significantly superior to the "2-segment fixed end" algorithm (p = 0.006)[4] and marginally significantly superior to the "2-segment fixed start" algorithm (p = 0.058)[4]. However, mean rankings were not significantly different for reader 2 (Friedman's test, p = 0.098; Table 1).

The mean rank of the three reconstructed image sets from scanner 1 separated by HR is summarized for each reader in Table 2. Reader 1's preference for the single-segment algorithm was consistent across all three HR groups (Table 2). However, statistically significant differences among the three reconstruction algorithms were only found by reader 1 for the lowest HRs (Friedman's test, p = 0.033; Table 2). Specifically, reader 1 showed a preference for the single-segment algorithm over the "2-segment fixed end" algorithm for HRs between 63 and 80 bpm (p = 0.048)[4].

Table 1. Comparison of mean ranking assigned to each reconstruction technique implemented on a 4-slice, 500 ms gantry rotation time scanner (n = 78). HR: heart rate.

Tabelle 1. Vergleich der Mittelwerte („mean rank") der Bildqualität für die verschiedenen Bildrekonstruktionen der mit Scanner 1 untersuchten Patienten (4-Schicht, 500 ms Gantry-Rotationszeit).

	Reconstruction technique			
	Single-segment	2-segment fixed start	2-segment fixed end	p-value
Reader 1	1.65 (50.0%)	1.97 (30.%)	2.13 (26.9%)	0.006
Reader 2	1.83 (30.8%)	1.71 (53.8%)	2.01 (33.3%)	0.098

Note: values are means (percentage of cases where technique was ranked #1). If there was a tie for #1 between two or more techniques, the case was included in the percentage for each of the techniques ranked #1. The p-values were determined from Friedman's two-way nonparametric test

Reader 2's preference varied according to HR: the single-segment algorithm was superior (though not statistically significant) for the lowest HR category (p = 0.598, Table 2) while the "2-segment fixed start" algorithm was superior for the moderate and highest HR categories (p = 0.436 and 0.033, respectively; Table 2) only reaching statistical significance for the highest HR categories; none of the pairwise comparisons reached statistical significance.

[4] p-values were adjusted for the number of pairwise comparisons.

Figure 4a – Abbildung 4a

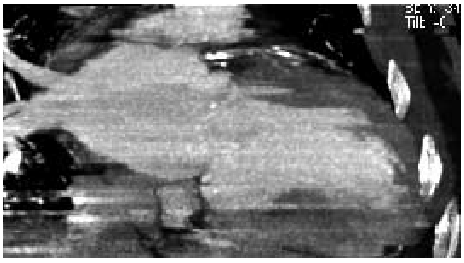


Figure 4b – Abbildung 4b

Figure 4c – Abbildung 4c

Figures 4a to 4c. Corresponding oblique maximum intensity projections from a typical patient with an average heart rate of 76 bpm imaged to rule out arrhythmogenic right ventricular dysplasia (ARVD) using a) single-segment, b) "2-segment fixed start", and c) "2-segment fixed end" techniques to reconstruct MSCT spiral data acquired with a 4-slice, 500 ms gantry rotation time scanner. Cardiac motion artifacts are not improved with either 2-segment reconstruction technique. Differences in image quality are subtle and preference is reader-dependent. No evidence was found to support the diagnosis of ARVD.

Abbildungen 4a bis 4c. Gepaarte schräge „Maximum Intensity"-Projektionen eines typischen Patienten mit einer durchschnittlichen Herzfrequenz von 76 Schlägen/min in a) Einzelsegment-, b) „2-segment fixed start"- und c) „2-segment fixed end"-Rekonstruktionstechniken unter Verwendung eines 4-Schicht-Systems mit 500 ms Gantry-Rotationszeit. Der Bewegungsartefakt lässt sich mit keiner der beiden 2-Segment-Rekonstruktionen reduzieren. Die Unterschiede in der Bildqualität sind gering, und die Bewertung ist untersucherabhängig. Die wegen des klinischen Verdachts auf eine arrhythmogene rechtsventrikuläre Dysplasie (ARVD) indizierte MSCT-Untersuchung ergab keine für die ARVD charakteristischen Veränderungen.

Overall, the data for patients imaged on scanner 1 suggest that the single-segment algorithm was preferred over the other algorithms for HRs between 63 and 80 bpm, and that the "2-segment fixed end" algorithm was the least preferred for all HRs. When differences in image sets were detected by a reader for an individual patient, readers often indicated that 2-segment images appeared blurry. Still, there is no clear statistical evidence that any one technique as implemented on scanner 1 was superior.

Scanner 2

Patients imaged on scanner 2 had an average HR of 81 ± 4.6 bpm. The mean rank of the image sets for these patients is summarized for each reader in Table 3. Both readers preferred the image quality achieved with 2-segment reconstruction over single-segment reconstruction for spiral imaging on scanner 2 (Figures 5a and 5b). Images reconstructed with the 2-segment algorithm were given a mean rank of 1.23 and 1.15 by readers 1 and 2, respectively, while images reconstructed with the single-segment algorithms were assigned mean ranks of 1.69 and 1.73, respectively (Table 3; Wilcoxon signed-rank test, $p < 0.01$ for both readers).

Discussion

Data from a group of cardiac patients obtained using a standard protocol for contrast-enhanced ECG-gated spiral MSCT on a 4-slice, 500 ms gantry rotation time scanner were reconstructed using three different algorithms. A partial-scan or single-segment reconstruction algorithm was compared to two different implementations of a 2-segment reconstruction algorithm. The single-segment reconstruction algorithm acquired 180° of parallel projection data during one cardiac cycle to create each image and resulted in a temporal resolution equal to approximately 250 ms. The 2-segment reconstruction algorithms required the same amount of data to create each image but utilized data from the same phase of two consecutive cardiac cycles to increase the effective temporal resolution to between 125–250 ms. Despite the increase in effective temporal resolution using segmented reconstruction techniques, corresponding improvements in image quality were not realized for this scanner for HRs ranging from 63 to > 100 bpm. Additionally, although "2-segment fixed end" techniques were the least preferred by both readers, no significant difference was observed between the two implementations of 2-segment reconstruction on a 4-slice, 500 ms rotation time scanner.

Table 2. Comparison by heart rate (HR) of mean ranking assigned to each reconstruction technique implemented on a 4-slice, 500 ms gantry rotation time scanner (n = 78). HR: heart rate.

Tabelle 2. Vergleich der Mittelwerte ("mean rank") der Bildqualität in Abhängikeit von der Herzfrequenz für die verschiedenen Bildrekonstruktionen der mit Scanner 1 untersuchten Patienten (4-Schicht, 500 ms Gantry-Rotationszeit).

	Reconstruction technique Single-segment	 2-segment fixed start	 2-segment fixed end	p-value
Reader 1				
63 < HR < 80	1.58 (53.8%)	2.04 (26.9%)	2.27 (23.1%)	0.033
80 < HR < 100	1.69 (50.0%)	2.08 (30.8%)	2.04 (23.1%)	0.273
HR > 100	1.69 (46.2%)	1.81 (34.6%)	2.08 (34.6%)	0.291
Reader 2				
63 < HR < 80	1.77 (50.0%)	2.00 (34.6%)	2.00 (34.6%)	0.598
80 < HR < 100	1.85 (30.8%)	1.65 (38.5%)	1.96 (19.2%)	0.436
HR > 100	1.88 (23.1%)	1.46 (73.1%)	2.08 (30.8%)	0.033

Note: values are means (percentage of cases where technique was ranked #1). If there was a tie for #1 between two or more techniques, the case was included in the percentage for each of the techniques ranked #1. The p-values were determined from Friedman's two-way nonparametric test

Table 3. Comparison of mean ranking assigned to each reconstruction technique implemented on a 12-slice, 420 ms gantry rotation time scanner (n = 26).

Tabelle 3. Vergleich der Mittelwerte ("mean rank") der Bildqualität für die verschiedenen Bildrekonstruktionen der mit Scanner 2 untersuchten Patienten (12-Schicht, 420 ms Gantry-Rotationszeit).

	Reconstruction technique Single-segment	 2-segment fixed start	p-value
Reader 1	1.69 (30.8%)	1.23 (76.9%)	0.011
Reader 2	1.73 (26.9%)	1.15 (84.6%)	0.0006

Note: values are means (percentage of cases where technique was ranked #1). If there was a tie for #1 between two techniques, the case was included in the percentage for each technique. The p-values were determined from the Wilcoxon signed rank test

A study by Kachelrieß et al [10] based primarily on theoretical considerations concluded that for HRs > 70 bpm, multi-segment reconstruction yields results superior to single-segment reconstruction when the table feed is restricted. Flohr & Ohnesorge [5] demonstrated an improvement in image quality using 2-segment reconstruction compared to single-segment reconstruction on a 4-slice, 500 ms scanner in a small group of patients. Although practical considerations with the scanner used in the study demanded a higher than ideal table feed, a reduction in image artifacts and improved depiction of anatomic structures was observed in select patients with 2-segment reconstruction. However, examination of a large cohort of patients in the current study

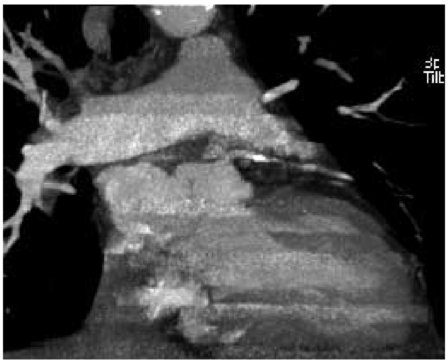


Figure 5a – Abbildung 5a

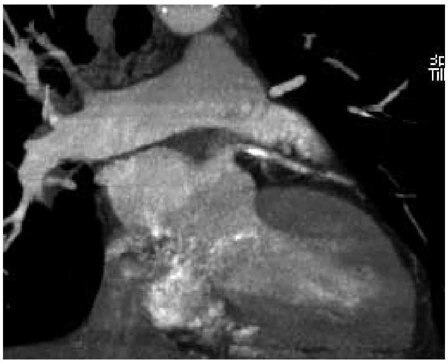


Figure 5b – Abbildung 5b

Figures 5a and 5b. Corresponding oblique maximum intensity projections from a typical patient with a heart rate of 84 bpm evaluated for pulmonary venous stenoses after radiofrequency ablation for atrial fibrillation. a) Single-segment and b) 2-segment techniques were used to reconstruct MSCT spiral data acquired with a 12-slice, 420 ms gantry rotation time scanner. 2-segment reconstruction provided images with reduced cardiac motion and improved delineation of cardiac structures and facilitated the finding of no significant pulmonary vein stenosis.

Abbildungen 5a und 5b. Gepaarte schräge „Maximum Intensity"-Projektionen eines typischen Patienten mit einer Herzfrequenz von 84 Schlägen/min. Indikation für die Untersuchung war der Ausschluss einer Lungenvenenstenose nach Radiofrequenzablation wegen Vorhofflimmerns. a) Einzelsegment- und b) 2-Segment-Techniken wurden zur Rekonstruktion von MSCT-Daten, die mit einem 12-Schicht-System und 420 ms Gantry-Rotationszeit aufgenommen wurden. Die 2-Segment-Rekonstruktion ermöglichte eine Verringerung des Bewegungsartefakts und eine verbesserte Darstellung der kardiovaskulären Strukturen. Die verbesserte Bildqualität erleichterte den Ausschluss einer signifikanten Pulmonalvenenstenose.

using a similar 2-segment approach on the same scanner failed to demonstrate a significant difference between 1- and 2-segment reconstruction. This result indicates that the limitations of multi-segment reconstruction including broadening of the TSP, broadening of the SSP, and dynamic definition of temporal resolution may have more of a negative impact on image quality than previously thought for n = 2 on a scanner acquiring 4 slices per rotation with t_{rot} = 500 ms.

First, the use of data from multiple gantry rotations can result in broadening of the SSP and spatial blurring of the image depending on the reconstruction position relative to the detector position [5, 10]. Although this should not be problematic for 2-segment reconstruction at low table feeds, the table feed used in this study with scanner 1 was likely too high for 2-segment reconstruction but was required to cover the heart in a reasonable breathhold.

Inconsistencies between heart cycles due to arrhythmia can also lead to broadening of the TSP. Multi-segment reconstruction algorithms assume periodic motion over n consecutive cardiac cycles. However, data from even two cardiac cycles obtained with the same temporal relation to the R-wave but with changing local HR could come from slightly different cardiac phases introducing the possibility of errors from data averaging or misregistration with resultant temporal blurring of the reconstructed image. For images reconstructed using single-segment techniques, data obtained from slightly different cardiac phases result in a timing shift from image to image giving two-dimensional or three-dimensional reformats a stair-step appearance. However, for images reconstructed using multi-segment techniques, the timing shift is incorporated into individual images reducing the stair-step appearance of reformats but at the expense of increased blurring within individual images.

Additionally, for the multi-segment algorithm implemented in this study, the temporal resolution is defined dynamically as a function of the HR at each reconstruction position. The variation in the temporal resolution of images across an image set is demonstrated for a patient with an extremely varying HR (Figure 6). During the scan the patient's HR oscillated between 50 and 120 bpm. Subsequently, the length of the data acquisition window and the effective temporal resolution fluctuated from image to image ranging between 128 and 250 ms. Such variations in the temporal resolution across an image set may actually degrade the quality of image reformats.

A second group of patients with HRs between 74 and 90 bpm was imaged with a scanner capable of acquiring twelve slices per rotation at a gantry rotation time of 420 ms. These patients were targeted because improved performance of 2-segment reconstruction was expected in this HR range with t_{rot} = 420 ms (Figure 2). Data from a standard protocol for ECG-gated spiral MSCT were reconstructed using single-segment and "2-segment fixed start" techniques; the "2-segment fixed end" algorithm was omitted from the comparison since no significant differences in implementation of the 2-segment algorithm emerged from the previous study. Improved image quality was obtained for scanner 2 using 2-segment reconstruction for the selected HR range.

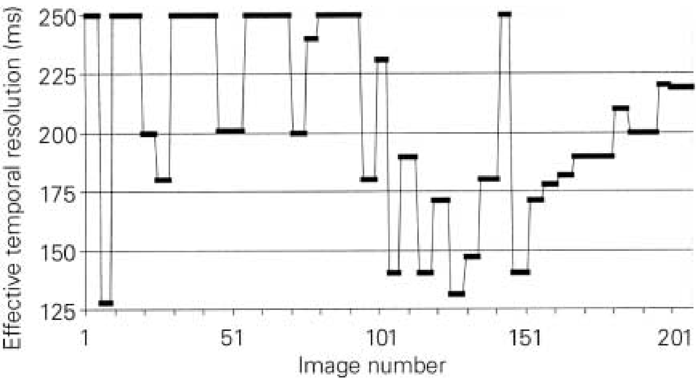


Figure 6. Patient with varying heart rate (HR) imaged on 4-slice CT scanner with fixed rotation time equal to 500 ms. Spiral data were acquired and reconstructed using a 2-segment reconstruction algorithm. During the scan the patient's HR averaged 72 bpm but oscillated between 50 and 120 bpm. Subsequently, the length of the data acquisition window used to create each image varied from 128–250 ms.

Abbildung 6. Patient mit fluktuierender Herzfrequenz (HR). Die Untersuchung erfolgte mit einem 4-Schicht-CT-System und fester Gantry-Rotationszeit von 500 ms. Nach Akquisition der Spiraldaten wurden diese mit einem 2-Segment-Algorithmus rekonstruiert. Während der Untersuchung fluktuierte die HR zwischen 50 and 120 Schlägen/min bei einem Mittelwert von 72 Schlägen/min. Die Länge des zur Bildrekonstruktion verwendeten Bildakquisitionsintervalls schwankte zwischen 128 und 250 ms.

A smaller variation in the SSP was achieved with multi-segment reconstruction on scanner 2 as a result of increased data sampling with a greater number of detectors. Therefore, spatial blurring of the reconstructed images was not as severe as for implementation of 2-segment algorithms on the 4-slice, 500 ms rotation time scanner.

Improved image quality with multi-segment reconstruction in the second group of patients may also be attributable to the overall improvement in temporal resolution (125–250 ms for t_{rot} = 500 ms vs. 105–210 ms for t_{rot} = 420 ms), especially for the HR range studied. Shorter reconstruction times more often permit ideal placement of the reconstruction window in diastole where cardiac motion is at a minimum. Further, temporal differences in data obtained during consecutive cardiac cycles resulting from HR inconsistencies are presumably less pronounced during this optimal diastolic period. Finally, although temporal resolution is defined dynamically as a function of HR as before, the length of the reconstruction window at t_{rot} = 420 ms varies over a narrower range introducing less variability between images.

Although the reconstruction of data from two consecutive cardiac cycles to effectively increase temporal resolution is a promising technique for reducing cardiac motion artifacts as implemented on 12-slice, 420 ms rotation time scanners, optimal selection of the cardiac phase may have a bigger impact on image quality. Several groups have demonstrated that the choice of reconstruction timing significantly affects the presence of cardiac motion artifacts for coronary artery imaging [8, 12]. For 4-slice, 500 ms rotation time scanners, cardiac motion artifacts were minimized at 50–70% R-R for LAD, 50–60% R-R for LCX, and 40–50% of the R-R interval for the RCA. Optimal timing of image reconstruction is presumably even more crucial with 420 ms rotation time scanners capable of increased temporal resolution (105–210 ms) although no additional studies have been performed to date on these scanners.

Conclusions

Limited temporal resolution is the major challenge for cardiac applications with mechanical MSCT. Efforts to improve temporal resolution with existing technology include the development of dedicated cardiac reconstruction algorithms, multi-segment algorithms, for spiral imaging that obtain the 180° of required parallel projection data from the same heart phase of consecutive cardiac cycles. Despite higher effective temporal resolution at certain HRs, the added value of 2-segment cardiac reconstruction for spiral MSCT was not demonstrated in cardiac patients as implemented on a 4-slice, 500 ms gantry rotation time scanner. However, 2-segment reconstruction did provide improved image quality compared to single-segment reconstruction for clinically important HRs ranging from 74–90 bpm on a 12-slice, 420 ms gantry rotation time scanner.

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