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# 심장 CT에서 다른 기계 간 시간 해상도 비교 및 관상동맥의 움직임 실측

# Actual Temporal Resolution of Cardiac CT from Different Scanners and Actual Coronary Artery Movement

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# Abstract

**Purpose:** To provide better understanding in acquisition and interpretation of cardiac CT by analyzing actual temporal resolution (TR) of MDCTs and actual coronary artery movement.

**Material and Methods:** The rotating phantom consisting of cylindrical polyethylene background with acetal cores was used. EKG gated cardiac CT scans of the phantom were taken under various protocols for four different CT machine on variable RPM with simulated EKG signals. Actual TR of the scan was calculated from the angle of the trace of acetal cores' motion. Biplane coronary angiography was obtained from 20 patients. The anteroposterial and true lateral projections were separated into serial bitmap still images and the eight landmarks from branching points were selected. The scale was corrected from the Z-axis value and was converted to absolute scale. The three dimensional velocities and total path distances for 100 ms were calculated for each point by vector analysis.

**Results:** The actual TR of cardiac scan was measured as 88.9 ms, 138.4 ms, 196.1 ms, 199.8 ms, 132.8 ms, and 90.8 ms from Siemens Somatom Definition Flash, Philips Brilliance iCT, GE

Discovery CT750 HD, Toshiba Aquilion, Phlips IQon Spectral, Siemens Somatom Force, respectively. The cardiac helical scan from Philips IQon Spectral demonstrated the smallest ratio of calculated TR to expected TR (0.98). Three dimensional coronary artery motion traced figure of eight. The maximum velocity from each patient ranged from 9.53 to 32.1 cm/sec (median: 19.9), all from RCA. During systolic phase, minimum coronary artery motion during 100 ms ranged from 1.3 to 5.7 mm (median: 2.8) at left main bifurcation and 1.5 to 7.4 mm (median: 3.8) at mid RCA; During diastolic phase, 0.45 to 5.6 mm (median: 2.2) and 0.57 to 7.1 mm (median: 1.8), respectively. If 1.5 mm of movement during scanning is defined as upper limit for tolerable motion free images, RCA showed 50% chance to be tolerable while LCA mostly remained tolerable during systolic phase when TR is 100ms. During diastolic phase, both RCA and LCA remained tolerable when HR was under 75 but RCA became intolerable when HR was higher.

**Conclusion:** Actual TR of cardiac CT scans demonstrated difference from expected TR. Regarding coronary artery movement, 100ms is still not enough for stable scan when HR is higher than 75.

Keywords: Temporal Resolution, Cardiac CT, Coronary artery,

Phantom study

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# INTRODUCTION

Temporal resolution (TR) has always been one of the major issues for cardiac CT imaging. Since the introduction of MDCT (1) accompanied with ECG-gated retrospective image collection enabled us to get coronary angiography from CT images, additional techniques designed by many different companies, such as dual source imaging or FLASH have shortened the temporal resolution of cardiac CT, now theoretically down to 66 ms (2, 3), proposed by Somatom Force.

We generally adopt the TR values from which CT manufacturers theoretically propose from rotation time reconstruction algorithm of the machine. However, in routine practice, there is sometimes a discrepancy between the theoretical TR and the degree of motion artifact. TR by definition is the time required to acquire certain image, and thus can be measured simply by the range of motion artifact if we know the speed of the subject. There have been many studies evaluating temporal resolution of MDCT comparing different reconstruction algorithms, but few studies actually measured TR and compared the values among different vendors.

In our study, we calculated actual TR by measuring the angle of the motion artifact a rotating phantom made. Furthermore, we acquired three-dimensional real-time movement data of coronary arteries from 2-plane cine images of conventional cardiac angiography. The purpose of our study was to provide the experimental data of TR of different CT protocols from different 4th generation MDCT vendors, and accompanied with real-time movement data of coronary arteries, to simulate the motion free acquisition of CT scan among the patient with different HR.

# MATERIALS AND METHODS

## Actual TR measurement from the rotating phantom

### *Rotating phantom*

A rotating phantom consisting of a polyethylene cylindrical background and ten acetal cores, of which the attenuation (-90HU and 300HU, respectively) was similar to that of the fat and soft tissue, was designed (Figure 1). Six of the cores were arranged along the X-axis and four along the Y-axis. The diameter of all cores was 10 mm, and the distance between the centers of the cores were 25, 25, and 25 mm in X-axis, respectively, and 35, and 25 mm in Y-axis, respectively. The rotation time (revolutions per minute, RPM) of the phantom was manipulated by manually rotating a lever (Figure 1).

### *Image acquisition and TR measurement*

The images were scanned by six CT vendors available in our hospital, GE Discovery CT750 HD, Toshiba Aquilion One (640 Series), Philips Brilliance iCT, Somatom Definition Flash, Phlips IQon Spectral, and Siemens Somatom Force. For each vendor, the images were taken for all available protocols used in routine practice, including both non-gated and ECG-gated cardiac protocols, under the field-of-view of 300 mm, the peak kilovolatage of 100kVp, and the peak tube current 150mAs. All ECG-gated cardiac CT scans were taken under the simulated EGC signal of which the HR was set as 60/min.

For each CT protocol, images were taken with various RPMs of the rotating phantom, 15, 30, and 60, and the optimal RPM was selected where the trace of motion artifact showed the core angle within 30 to 70 degree, in which the observer can most stably measure the angles while avoiding trace-overlapping. The core angle of the trace was measured by one radiologist (J.G.N. with 3 years of experience), eight times for each image: Under the cardiac widow setting (window width 1000 and window level 100), two points were selected where we can no longer trace the tract, and the imaginary circles were drawn at each point. The angle was measured between centers of those two circles (Figure 2).

After measuring the core angle of motion artifact rotating phantom made ($\theta$), actual TR was calculated by following equation.

$$\mathrm{TR} = \frac{\mathrm{time}}{\mathrm{RPM\ (rotation\ time\ /sec)}} = \frac{1}{\mathrm{RPM}} \mathrm{x} \frac{\theta}{360}$$

## Coronary Artery Motion Analysis

Twenty consecutive patients (M:F=13:7, mean age [range] of 55 [44-72]), who underwent biplane coronary angiography were retrospectively included. The institutional review board of Seoul National University Hospital approved the study and the requirement for informed consent was waived.

### *Velocity analysis*

The anteroposterial projection image and true lateral images were acquired simultaneously with biplane coronary angiography (Phillips, Netherlands) for more than 5 seconds at the frame rate of 30 f/s. The cine angiographies were obtained with breath-hold to eliminate the respiratory movement. The acquired cine images are separated to serial bitmap still images by ACOM PC (Siemens, Germany) software from R-peak to next R-peak of the concurrently recorded EKG signal. Total four sets of 20-35 still images of one R-R interval are analyzed. Total eight landmarks from branching points were selected; four at basal segment and four at mid to apical segment were pointed as 2D coordinates scene by scene by UTHSCSA ImageTool (Texas, USA) software (Figure 3). The landmarks are os of left anterior descending artery (LAD), os of obtuse marginal (OM) branch, os of acute marginal (AM) branch, os of posterior descending artery (PDA) and four mid to apical branching point of LAD, OM, AM, and PDA, respectively. The two sets of coordinates are obtained for each landmark. The zoom factors and absolute locations of both coordinates are different due to both projections have different zoom factor and position. The scale alignments and zoom factor are corrected by comparing distribution of the value of Z-axis coordinates, which is expected same on both view point by Levenberg-Marquardt routine. Finally, three dimensional coordinates are obtained. The three dimensional velocities of each points are calculated by vector analysis.

### *Motion Free Acquisition of Coronary Arteries*

Under the assumption that best achievable TR for cardiac CT scans are around 100 ms, the total path distance for 100 ms were obtained point by point. The path distance presented by pixel was converted to absolute mm scale by using the diameter of catheter for angiography.

# RESULTS

## Actual TR measurement from the rotating phantom

The shortest actual TR from each CT vendors was calculated as 88.9 ms, 90.8 ms, 132.8 ms, 138.4 ms, 196.1 ms, and 199.8 ms, from Siemens Somatom Definition Flash, Siemens Somatom Force, Phlips IQon Spectral, Philips Brilliance iCT, GE Discovery CT750 HD, and Toshiba Aquilion, respectively (Table 1). The cardiac helical protocol from Siemens Somatom definition FLASH demonstrated the shortest TR, 88.9 ms, and the TR from each cardiac protocol from each CT machine ranged from 88.9 ms to 208.8 ms range (Table 1). Standard deviation of measured eight values arranged 1.9 ms to 7.8 ms. The abdominal sequential and cardiac helical scan from Toshiba Aquilion were not obtained as they are not used in routine practice.

The ratio of actual calculated TR to expected TR was also evaluated for each protocol. The expected TR is taken from reference value proposed by each company. The cardiac helical scan from Philips IQon Spectral demonstrated the smallest ratio of calculated TR to expected TR (0.98) among all cardiac scan protocols. Beside this sequence, the ratio of calculated TR to expected TR remained bigger than 1 among all cardiac CT protocols. The biggest calculated TR to expected TR ratio was 1.48, taken from sequential scan from Simens Somatom Force. While all other scanners showed shorter calculated TR using helical scan, Phillips Brilliance iCT demonstrated shorter TR using sequential scan. The dual energy scan from GE Discovery CT750 HD showed better TR (191.0 ms) than helical and sequential scans (196.1 and 208.8 ms, respective), though all three protocols had same expected TR value (175 ms).

## Coronary Artery Motion Analysis

The mean distribution of heart rate of patient at the time of angiography was 69 beats per minute (bpm), ranged 53 to 88 bpm. In three-dimensional coordinates, coronary artery traced the figure of eight during each heartbeat (Figure 5).

## *Velocity analysis*

The maximum velocity from each patient ranged from 9.53 to 32.1 cm/s (median: 19.9, average: 20.2), all from RCA (ten patients from ostium (os) of acute marginal branch, six patients from distal acute marginal branch, and other four patients from PDA os).

Given that the best TR would be around 100 ms by rotating phantom experiment, integral velocity curve was obtained for 100ms time-interval for each patient. During systolic phase, minimum coronary artery motion during 100 ms ranged from 1.3 to 5.7 mm (median: 2.8) at left main bifurcation and 1.5 to 7.4 mm (median: 3.8) at mid RCA; During the diastolic phase, 0.45 to 5.6 mm (median: 2.2) and 0.57 to 7.1 mm (median: 1.8), respectively.

## *Motion Free Acquisition of Coronary Arteries*

Regarding the normal diameter of RCA and LM to be 3 to 5 mm in size (4), we considered the path distance less than 1.5

mm to be tolerable as motion free acquisition from previous report which set motionless threshold as 1mm (5). RCA showed about 50% chance to be tolerable while LCA mostly remained tolerable during systolic phase when TR is 100ms. During diastolic phase, both RCA and LCA remained tolerable when HR was under 75 but RCA became intolerable when HR was higher (Figure 6). We defined the motion free acquisition window as the time interval in which the motion of the certain coronary artery movement was less than 1.5 mm during one cardiac scan. Figure 7 demonstrates the change of motion free acquisition window among the patients with different HR, when TR was set 100 ms and 200 ms. The diastolic motion free acquisition window sufficient in the patient with heart rate of 55 bpm. With heart rate of 62 the diastolic motion free acquisition window is shortened but there is still remained window for 100ms and 200ms. When the heart rate exceeds 70, the diastolic window does not different from that of systolic phase, so the coronary artery can be imaged without motion artifact only with high temporal resolution less than 100ms. In the patients with heart rate bigger than 80, the diastolic motion free acquisition window disappeared.

Figure 8 shows the motion free acquisition window of one representative patient, measured on all eight points. The mid to apical segment coronary artery shows longer resting period than basal segment coronary artery. Although there was no interval every eight points remain motionless, two intervals, systolic and diastolic respectively, coronary arteries remained less dynamic.

# DISCUSSION

Actual TRs of cardiac CT scans demonstrated some difference from the expected TRs. The ratios of calculated TRs to expected TRs were relatively tolerable (0.98 to 1.48), but the actual TRs were measured bigger than the expected value for all cardiac scans except for helical scan from Philips IQon Sepctral scanner. As the ratios were different among the protocols, the actual TR measurement can provide a reliable index comparing the TR of protocols from different vendors.

The shape of the artifact rotatory movement made was also interesting. Instead of the real trajectory the phantom made, the motion artifact featured either clockwise or counterclockwise spirals, depending on the concordance of the direction of rotation phantom and gantry made (eFigure 1). This kind of spiral-shaped motion artifacts is actually often seen in interpreting cardiac CT, especially for RCA branches (eFigure 2). In protocols using dual energy method or FLASH, motion artifact became more complex, figured the summation of clockwise and counterclockwise spirals (eFigure 1). In routine practice, the shape of motion artifact might be also important as complex shadow will blur the image more.

Expected TR is proposed by the manufacturers simply calculated from rotation time and the rotation angle theoretically needed for the reconstruction (6). However, as scanners are using complex reconstruction algorithms, actual motion artifact during each TR reflected on the image might be more complicated. For example, some scanners take full 360° scan first and then use half information afterwards, and more advanced techniques such as dual source, dual energy, or FLASH imaging also may exhibit unexpected degree or shape of motion artifact. As result, calculated TR from the motion artifact rotating phantom made produced slightly different values from expected TR and also showed various patterns of motion artifacts. As motion artifact rather than theoretical TR itself is what matters when reading the images, measuring actual TR might be valuable in terms of evaluating and comparing practical TRs from different scanners.

Our coronary artery motion analysis revealed that human coronary arteries, especially RCA, demonstrated high speed, ranging from 9.53 to 32.1 cm/s. This values correlate with previous measurement from coronary CT which reported peak velocity from RCA to be 0.1-33.4 cm/s (7). Concerning the pattern of coronary artery movement and the temporal resolution of CT, it would be beneficial to obtain diastolic images when HR is under 75 and systolic images when HR is faster. Also, as there seldom was the time interval every eight points remained motionless, it is important to understand various features of motion each CT protocol makes and not to be confused by them. Our results correlated with a previous study which reported that for patients with a heart rate of $< 70$ motion scores were significantly lower in the diastole phase than in the systole phase while in most patients with a heart rate of $> 80$ bpm, motion scores were lower in the systolic phase (6-8).

Our study has some limitations. First, as the actual TR measurement was performed using simple rotation, the pulsating coronary arteries might show different effects.

Also, the effect of the movement in Z-axis was not evaluated. Second, actual measurement of TR using rotating phantom might show discrepancy to the subjective degree of image blurring: as mentioned earlier, the degree of image blurring affecting the interpretation may depend more on the shape of the motion artifact rather than the temporal resolution itself. Further study comparing measured TR with subjective degree of motion artifact might be valuable. Last, as our study only included small number of patients retrospectively in evaluating coronary artery movement, it is difficult to provide general information

In conclusion, actual TRs of cardiac CT scans demonstrated some differences from expected TRs. Regarding coronary artery movement, 100ms is still not enough for stable scan when HR is higher than 75.

**Table 1: Calculated Temporal Resolution and Expected Temporal Resolution of each protocol from each CT machine**

| Protocol | | | GE Discovery CT750 HD | Toshiba Aquilion One | Philips Brilliance iCT | Siemens Somatom Definition Flash | Philips IQon Spectral | Siemens Somatom Force |
|---|---|---|---|---|---|---|---|---|
| **Shortest rotation time of vendor [ms]** | | | 350 | 350 | 270 | 280 | 270 | 250 |
| **Non-gated** | **Helical** | Actual* [ms] | 422.8 (0.85) | 741.5 (1.48) | 611.4 (1.53) | 812.9 (1.63) | 362.3 (1.10) | 842.3 (1.68) |
| | | Expected [ms] | 500.0 | 500.0 | 400.0 | 500.0 | 330.0 | 500.0 |
| | **Sequential** | Actual* [ms] | 573.8 (1.15) | | 469.0 (1.17) | 574.5 (1.15) | 836.5 (2.53) | |
| | | Expected [ms] | 500.0 | | 400.0 | 500.0 | 330.0 | |
| **ECG-gated cardiac** | **Helical** | Actual* [ms] | 196.1 (1.12) | | 141.3 (1.05) | 88.9 (1.18) | 132.8 (0.98) | 90.8 (1.38) |
| | | Expected [ms] | 175.0 | | 135.0 | 75.0 | 135.0 | 66.0 |
| | **Sequential** | Actual* [ms] | 208.8 (1.19) | 199.8 (1.14) | 138.4 (1.03) | 108.7 (1.45) | 173.2 (1.05) | 93.6 (1.42) |
| | | Expected [ms] | 175.0 | 175.0 | 135.0 | 75.0 | 165.0 | 66.0 |
| | **DE** | Actual* [ms] | 191.0 (1.09) | | | 155.2 (1.11) | | 146.9 (1.18) |
| | | Expected [ms] | 175.0 | | | 140.0 | | 125.0 |

| | | | |
|---|---|---|---|
| **Flash** | Actual* [ms] | 107.2 (1.29) | 97.4 (1.48) |
| | Expected [ms] | 83.0 | 66.0 |

*Data presented as actual temporal resolution (ratio), while ratio representing the actual Temporal resolution divided by expected temporal resolution

*DE Dual Energy*

Figure 1] The diagram of the rotating phantom with detailed scales. The background was made of polyethylene and the cores were made of acetal.

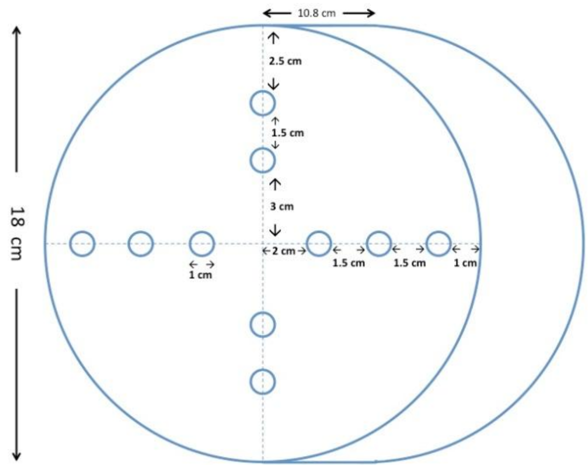


Figure 2] An example of the angle of motion artifact measurement. Under the common window setting, two points were selected until where no longer traceable and the imaginary circles were drawn at each point. The angle between centers of those two circles was measured.

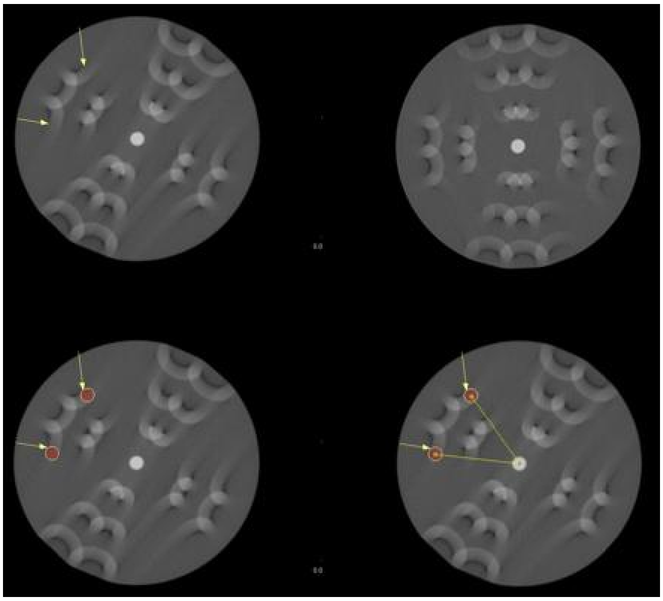


Figure 3] An example of plotting the landmarks on stacks of still images. Each of the eight points was marked scene by scene in both two-dimensional viewpoints. The ostium of acute marginal branch (arrowed) and ostium of posterior descending artery (arrowhead) are shown.

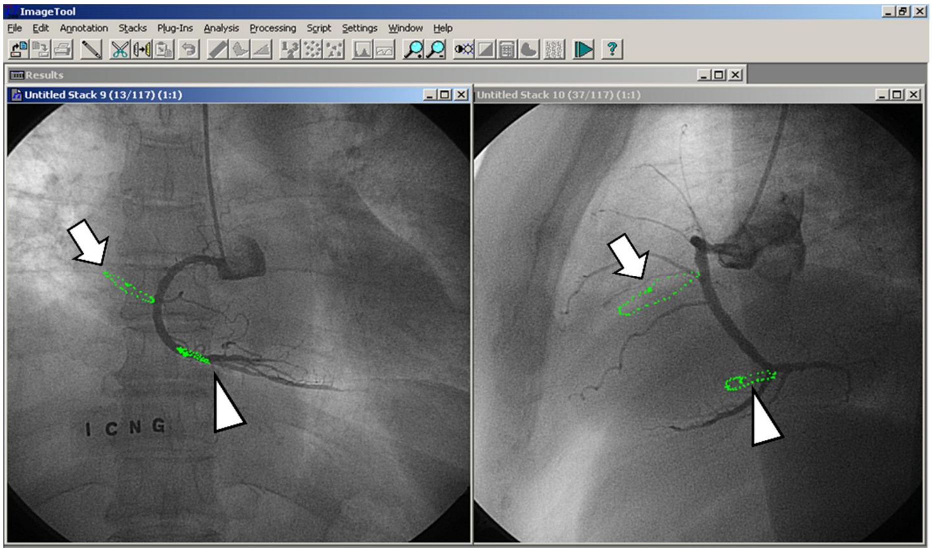
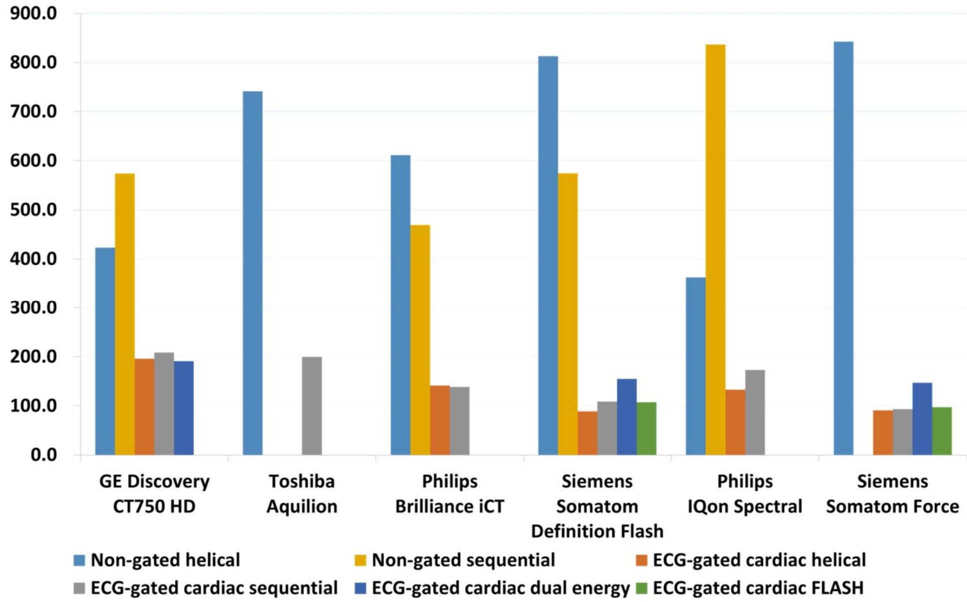


Figure 4] Calculated temporal resolutions (A) and calculated temporal resolution to expected temporal resolution ratios (B) evaluated from different protocols from the different scanners.



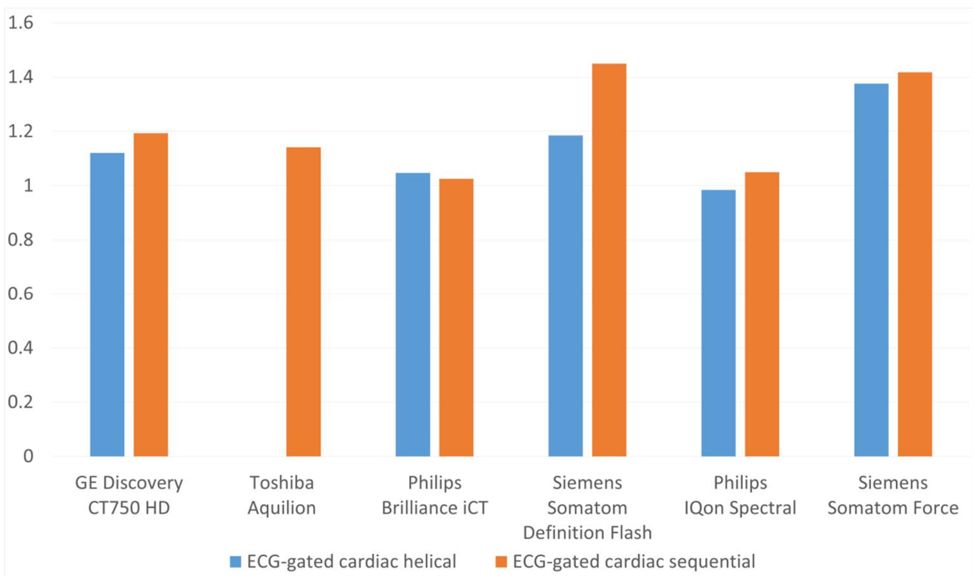



Figure 5] The three-dimensional coordinate of point plotted on space coordinate system. The selected point shows different pathway during systolic and diastolic phase. The movement of the point is projected on to the each XY, YZ, XZ plane.

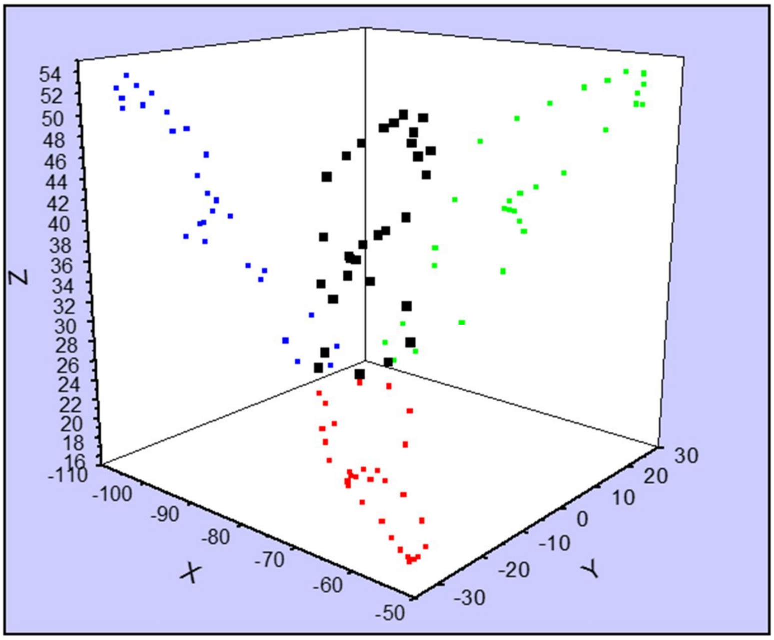


Figure 6] The length of motion free acquisition windows for 100ms according to the heart rates. The length of diastolic motion free acquisition windows markedly decreased when heart rate increased. No patients with heart rate >75 demonstrated possible motion free acquisition window on right coronary artery. The systolic motion free acquisition windows were not affected by heart rates.

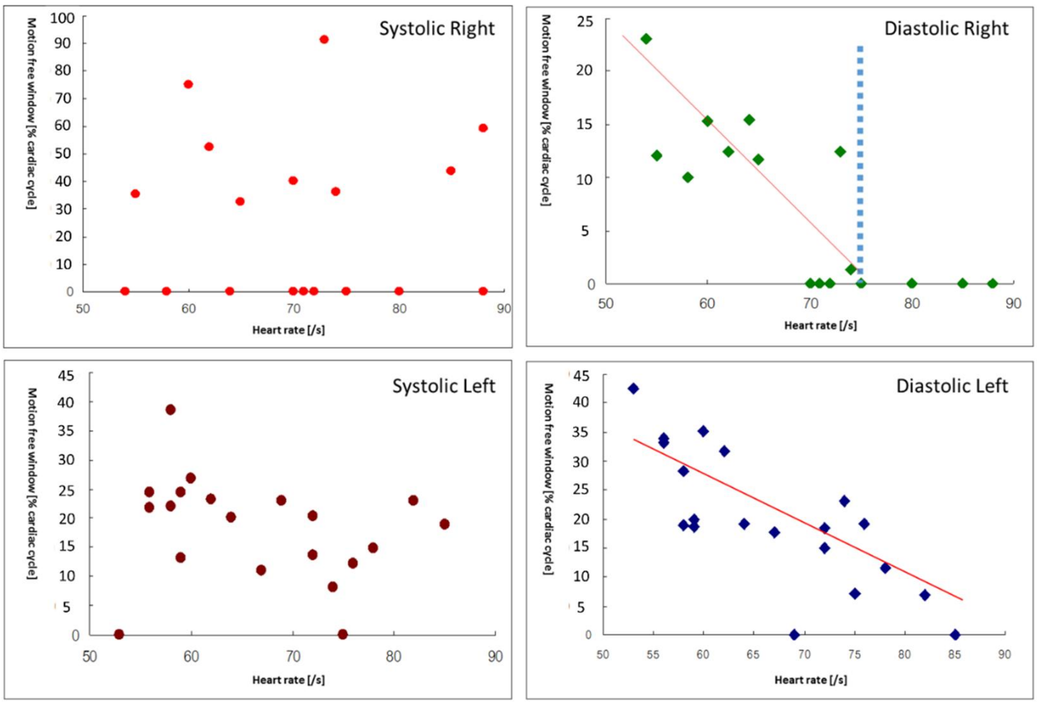


Figure 7] The integral velocity curve from four patients with different heart rates. Note the change of the motion free acquisition windows (arrows) in accordance with the heart rate. The diastolic motion free acquisition window sufficient in the patient with heart rate of 55 bpm. With heart rate of 62 the diastolic motion free acquisition window is shortened but there is still remained window for 100ms and 200ms. If the heart rate exceed 70 the diastolic window does not different from that of systolic phase, so the coronary artery can be imaged without motion artifact only with high temporal resolution less than 100ms. In the patients with heart rate over 80, the diastolic motion free acquisition window disappeared.

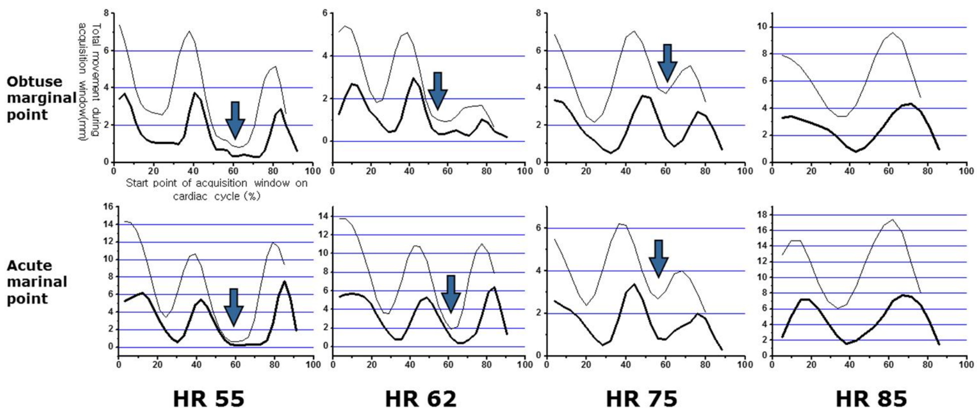
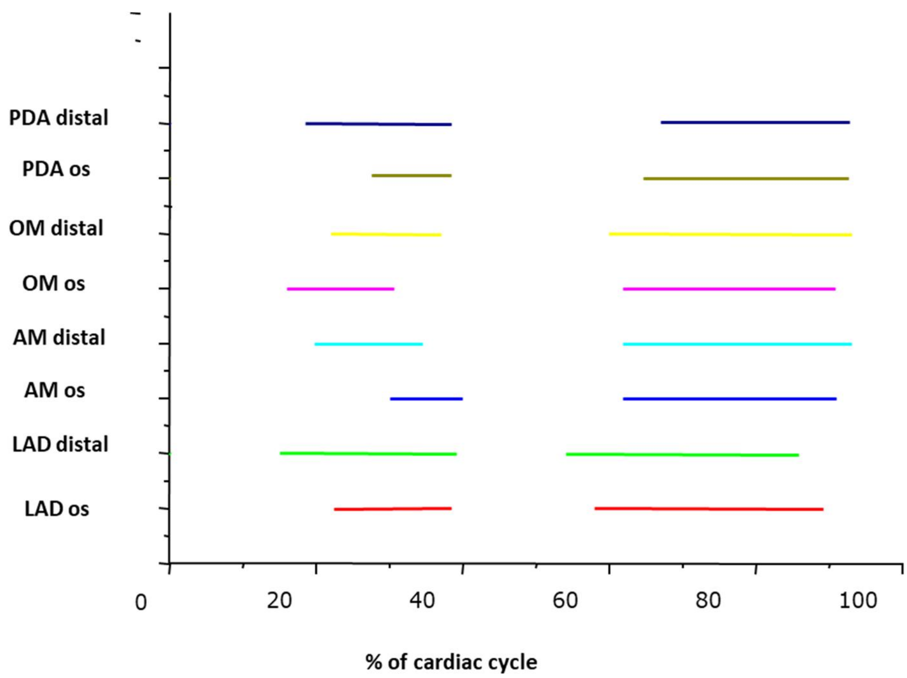


Figure 8] The motion free acquisition window of a representative patient. The starting point of acquisition window in which the total movement for 100ms was less than 1.5mm consider as motion free acquisition window. The ranges of motion free acquisition window of eight point were plotted. There were two motion free acquisition window; one in systolic phase and the other in diastolic phase.



# References

1. Begemann P, Van Stevendaal U, Manzke R, et al. Evaluation of spatial and temporal resolution for ECG-gated 16-row multidetector CT using a dynamic cardiac phantom. European radiology. 2005;15(5):1015-26.

2. Petri N, Gassenmaier T, Allmendinger T, Flohr T, Voelker W, Bley TA. Influence of cardiac motion on stent lumen visualization in third generation dual-source CT employing a pulsatile heart model. The British journal of radiology. 2017;90(1070):20160616.

3. Petersilka M, Bruder H, Krauss B, Stierstorfer K, Flohr TG. Technical principles of dual source CT. European journal of radiology. 2008;68(3):362-8.

4. Dodge J, Brown BG, Bolson EL, Dodge HT. Lumen diameter of normal human coronary arteries. Influence of age, sex, anatomic variation, and left ventricular hypertrophy or dilation. Circulation. 1992;86(1):232-46.

5. Johnson KR, Patel SJ, Whigham A, Hakim A, Pettigrew RI, Oshinski JN. Three□dimensional, time□resolved motion of the coronary arteries. Journal of

Cardiovascular Magnetic Resonance. 2004;6(3):663-73.

6. Lewis MA, Pascoal A, Keevil SF, Lewis CA. Selecting a CT scanner for cardiac imaging: the heart of the matter. The British journal of radiology. 2016;89(1065):20160376.

7. Husmann L, Leschka S, Desbiolles L, et al. Coronary artery motion and cardiac phases: dependency on heart rate—implications for CT image reconstruction. Radiology. 2007;245(2):567-76.

8. Seifarth H, Wienbeck S, Pu¨sken M, et al. Optimal systolic and diastolic reconstruction windows for coronary CT angiography using dual-source CT. American Journal of Roentgenology. 2007;189(6):1317-23.

# 요약

심장 CT 촬영에 있어서 시간 해상도는 영상의 질에 매우 중요하다. 보통 각 장비의 시간해상도는 기계 회사에서 제공하는 이론적인 값을 사용하고 있으며 현재까지 각 심장 CT 기계 및 촬영 기법에 따른 시간 해상도를 움직임 인공물을 이용해 실측한 연구는 거의 없었다. 이번 연구에서는 회전운동을 하는 모형 (phantom)을 사용하여 각 장비, 각 촬영 기법에서의 시간해상도를 직접 계산하였고 이론치와 비교하였다. 더불어 20명 환자들의 혈관조영술 영상을 통해 관상동맥 움직임을 3차원적으로 재구성하였고 대표적 8군데 지점에서의 움직임 및 속도를 분석하였다.

실측한 최소 시간 해상도는 Siemens Somatom Definition Flash, Philips Brilliance iCT, GE Discovery CT750 HD, Toshiba Aquilion, Phlips IQon Spectral, Siemens Somatom Force에서 각각 88.9 ms, 138.4 ms, 196.1 ms, 199.8 ms, 132.8 ms, 90.8 ms으로 측정되었고 Philips IQon Spectral의 심장 helical 기법이 가장 낮은 실측 시간 해상도 대 예측 시간 해상도 값을 나타냈다 (0.98). 관상동맥은 3차원적으로 8자 모양을 나타냈고 20명 환자에서 가장 빠르게 움직이는 지점은 모두 우관상동맥에서 관찰되었고 최고속도는 9.53에서 32.1 cm/sec (중간값: 19.9)으로 나타났다. 100 ms에서의 움직임을 보면 좌관상동맥 분기점에서 1.3에서 5.7 mm (중간값: 2.8), 우관상동맥 중간 지점에서 1.5에서 7.4 mm (중간값: 3.8)으로 관찰되었다. 시간 해상도 100 ms

수준에서 촬영 시간 동안 관상동맥 지름의 반 정도인 1.5 mm 정도의 움직임을 "판독 가능" 한 최대 움직임으로 가정하였을 때, 심장 수축기의 경우 우관상동맥은 50%정도, 좌관상동맥의 경우 대부분의 환자들이 "판독 가능" 한 움직임을 보였다. 심장 이완기의 경우, 심장박동수가 75/min 이하 환자들에서는 좌우 관상동맥 모두 "판독 가능" 한 움직임을 보였고 75/min 이상인 경우 모두 "판독 가능" 하지 못했다.

결론: 실측한 시간해상도는 실제 예측치와 다소 차이를 보였으며, 실제 관상동맥 움직임을 보았을 때 100 ms의 시간해상도는 심박동수 75 이상 환자에서 "판독 가능"한 영상을 얻기에 불충분하다.

**주요어: 시간 해상도, 심장 CT, 관상동맥, 모형 연구**

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