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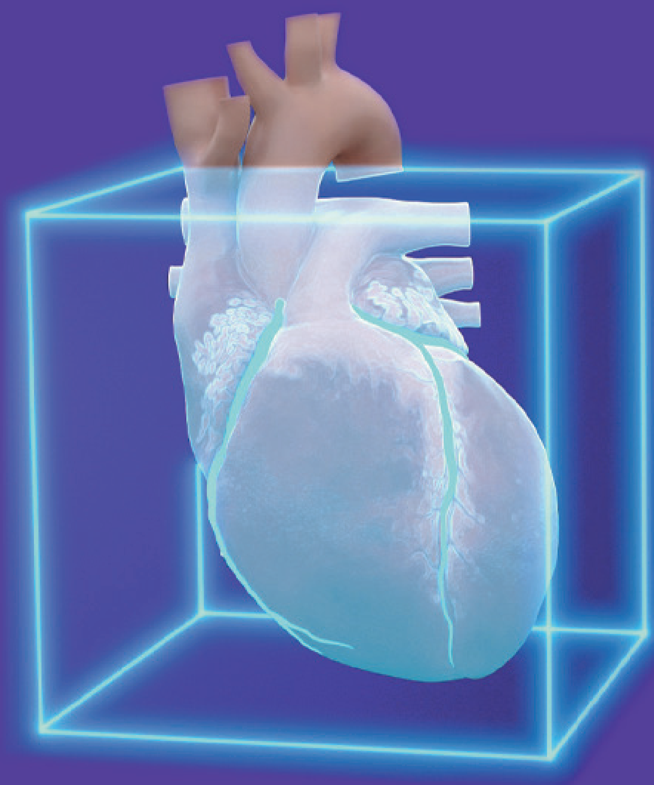

The Next Generation of Intelligent Cardiac Motion Correction: SnapShot Freeze 2

Technical and clinical white paper on cardiac CT image reconstruction

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Content

1. Background

In recent years, multiple clinical trials have demonstrated how cardiac CT used as a front-line test can provide a reliable diagnostic tool and help improve clinical outcomes for patients (e.g., SCOT-HEART, Scottish Computed Tomography of the HEART [1], PROMISE, Prospective Multicenter Imaging Study for Evaluation of Chest Pain [2], and CONSERVE, Coronary Computed Tomographic Angiography for Selective Cardiac Catheterization [3]).

As a result, it has been incorporated into several clinical practice guidelines. In 2016, the National Institute of Health and Care Excellence (NICE) in the UK added coronary computed tomography angiography (CCTA) as the "first test for low-risk, stable chest pain patients without known history of coronary artery disease (CAD)" [4]. The European Society of Cardiology Clinical Practice guidelines on Chronic Coronary Syndromes acknowledged the role of CCTA as a "first-line tool for evaluation of chronic coronary syndromes for low- to intermediate-risk patients" (class I, level of evidence B recommendation).[5]. The 2021 AHA/ACC/ASE/CHEST/SAEM/SCCT/SCMR* Guideline for the Evaluation and Diagnosis of Chest Pain recommended CCTA at the highest class I, level of evidence A as the first line test for evaluating stable chest pain in intermediate-to-high risk patients with no known CAD [6].

The growing evidence for the utility of CCTA and the addition of CCTA in guidelines has resulted in increasing global utilization of cardiac CT. For example, in the United States, the number of CCTA procedures has increased from 1.6 Million to 5 Million (+275%) in one year from 2022 to 2023 [7].

While the rapid adoption of cardiac CT imaging and the underlying technical advances over the last two decades have been impressive, cardiac motion artifacts have remained a challenge in general, potentially resulting in reduced clinician confidence when reading cardiac CT images.

In this paper, we discuss the recent advances in SnapShot Freeze (SSF) technologies that refine cardiac imaging by expanding the breadth of intelligent motion correction applications. Worldwide users and researchers have conducted multiple studies to evaluate its diagnostic performance in Cardiac CT imaging. This white paper summarizes the evidence from key studies to provide references for practitioners incorporating this SSF technology into their clinical practice.**

2. Challenges of Cardiac Motion in Cardiac CT Imaging

Technical developments in CT systems have improved the temporal resolution of image acquisition through increased gantry rotation speed, larger detector coverage, or dual-source approaches. However, residual cardiac motion remains a persistent barrier to obtaining consistent, robust, and high-quality imaging in challenging conditions such as patients with high or variable heart rates and patients with a larger body size. Indeed, cardiac motion artifacts are a frequent source of significant image quality degradation when imaging the coronary arteries, valves, and other cardiac structures. This motion can influence the accurate assessment of coronary arteries and degrade the image quality for cardiac evaluation.

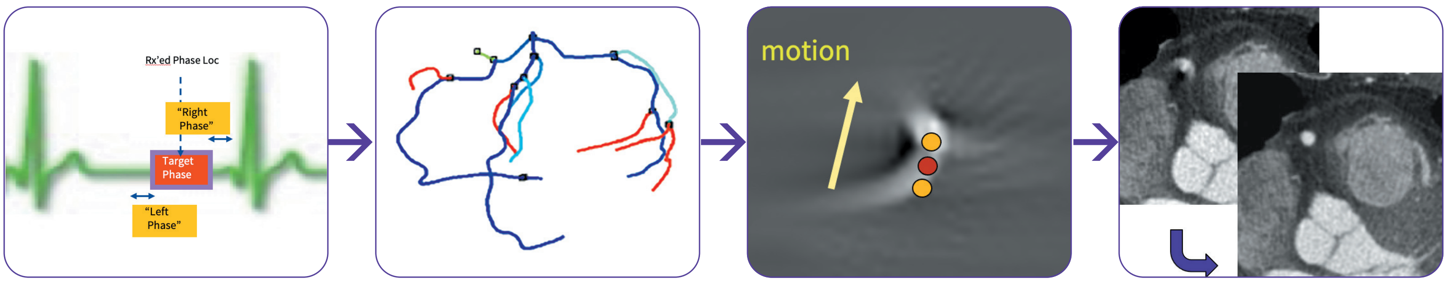
At 75 bpm, a right coronary artery (RCA) traveling at 35 mm/s, imaged with a 75 ms temporal resolution, yields vessel movement of 2.6 mm (0.075s * 35 mm/s) during the acquisition window. For a 3 mm diameter RCA, that degree of motion is nearly equal to the size of the coronary vessel itself.

Even though advances in CT hardware over time have improved the image quality in cardiac CT, it is essential to have access to intelligent motion correction that can be applied following the cardiac acquisition to compensate for any residual cardiac motion.

* American Heart Association/American College of Cardiology/American Society of Ecocardiography/American College of Chest Physicians (CHEST)/Society for Academic Emergency Medicine/Society of Cardiovascular Computed Tomography/Society for Cardiovascular Magnetic Resonance
** Most of the publications cited in are single center studies and varied by clinical indications, study protocols and comparison methods. The results and conclusions obtained in these studies are only applicable to the specific studies cited and may not be generalizable or reproducible in your practice.
Images in this white paper are not from the publications cited. These are additional sample images from clinical use.

3. SnapShot Freeze: a Revolutionary Approach in Cardiac CT Imaging

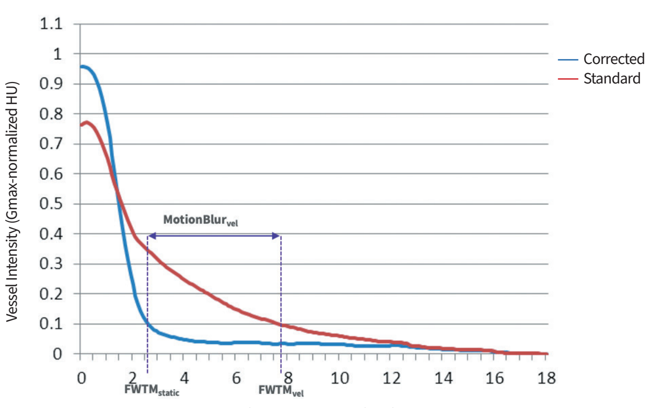
In 2012, GE HealthCare introduced SSF, the first intelligent motion-correction algorithm. This intelligent motion correction technology employs a novel image reconstruction and processing methodology that addresses the inherent limitations of a hardware-only solution. Following multi-phase cardiac reconstructions and automated coronary vessel tracking, SSF exploits information from adjacent cardiac phases within a single cardiac cycle to characterize vessel motion (both path and velocity) to determine the actual vessel position at the prescribed target phase (Figure 1). This adaptively compensates for any residual motion at that phase, effectively compressing the reconstruction temporal window. SSF works on per-vessel and per-segment basis to correct for differing degrees of motion of each voxel within the coronary vessels.

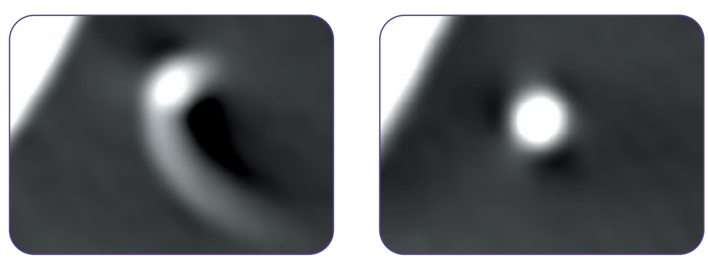


a) Multi-Phase Reconstruction
b) Advanced Processing
c) Motion Characterization
d) Motion Correction

Figure 1: Primary components of first generation SnapShot Freeze software for coronary motion correction. (a) Images acquired during multiple phases of the cardiac cycle are reconstructed. (b) Software automatically tracks coronary vessels across adjacent cardiac phases. (c) Vessel path and velocity are characterized. (d) SnapShot Freeze applies the calculated vessel motion on a per-vessel and per-segment basis and corrects each voxel of the images.

To assess SSF motion correction performance, a phantom study was conducted utilizing a cardiac phantom with attached tubular vessels modeling the coronaries. The model's chambers and vessels with 2, 3, 4, and 5 mm inside diameters were filled with iodine-based contrast. The phantom followed a typical motion profile for chamber displacement and was scanned with a 0.35s/rotation Snapshot Pulse acquisition. By selecting a location in the cardiac cycle, the vessels were imaged at average velocity of 10, 17, 33, 53, and 65 mm/s. Motion artifact was assessed versus a static, ground-truth baseline. To account for variation due to the gantry angle of the start of the exposure, multiple scans were acquired at various, randomized start angles. To quantify the magnitude of motion artifact, a radial full-width, tenth-max (FWTM) metric was employed such that the maximum radial distance from the center of the vessel to the point of 10% lumen intensity of the max HU of the static vessel reference was recorded (Figure 2). Vessel motion blur at a specific velocity is defined as: $\text{Motion Blur}_{vel} = \text{FWTM}_{vel} - \text{FWTM}_{static}$.





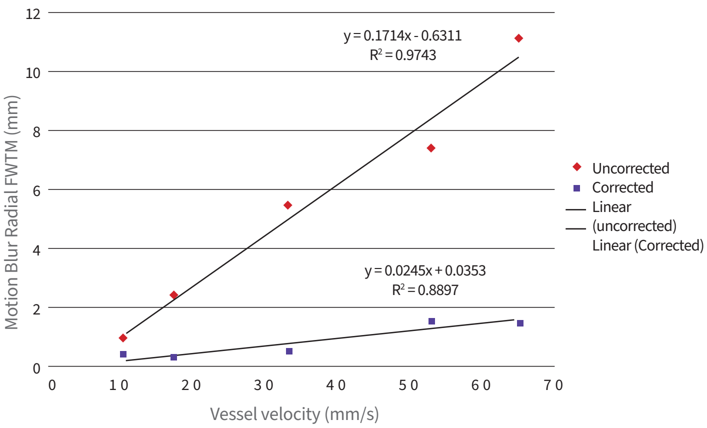
Uncorrected

SSF Corrected

Uncorrected	SS Freeze Corrected
Motion Blur (mm)	Motion Blur (mm)
5.43	0.42

Figure 2: Measurements of a 2 mm vessel (with a 1.2 mm vessel wall) at FWTM showing uncorrected and corrected images. FWTM: full-width, tenth-max.

The results of this phantom study show that, with SSF, coronary motion of a vessel can be reduced by an average factor of 6 (Figure 3).



Radial FWTM-based Motion Blur vs. Vessel Velocity					
	Uncorrected		SS Freeze Corrected		
Average Velocity (mm/s)	Radial FWT-M(mm)	Motion Blur (mm)	Radial FWMT (mm)	Motion Blur (mm)	Motion Reduction Factor
65	13.95	11.14	4.36	1.55	7.2
53	10.22	7.41	4.38	1.57	4.7
33	**8.25**	**5.44**	**3.42**	**0.61**	**8.9**
17	5.22	2.41	3.14	0.34	7.1
10	3.77	0.96	3.26	0.46	2.1
Average					**6.0**

Figure 3: Motion blurring for a 3 mm vessel from 10-65 mm/s. The results of this phantom study show that with Snapshot Freeze, coronary motion of a vessel moving at average of 33 mm/sec can be reduced by an average factor of 6 or more.

Since its introduction, a wealth of clinical studies has established the effectiveness of SSF technology [8-27], demonstrating its ability to enhance both image quality and diagnostic accuracy. In one of the initial studies, Pontone et al. [18] evaluated the impact of SSF on overall evaluability and diagnostic accuracy of CCTA in 160 patients scanned on a 4 cm scanner (101 male; mean age: 65.3 ± 11.7 years; mean heart rate: 68.3 ± 9.4 bpm; heart rate variability: 4.9 ± 6.2 bpm) with at least one coronary segment classified as non-evaluable for motion artifacts, by reconstructing data sets with and without motion correction. While the application of SSF had no significant impact on image noise, it reduced the number of artifacts (61% with SSF vs. 77% without SSF; p<.01), increased image quality score (mean score: 3.1 ± 0.9 vs. 2.5 ± 1.1; p<.01) and overall evaluability (94% vs. 79%; p<.01). It also led to a significant reduction of non-evaluable patients (from 18 % to 7%; p<.01) and, in a sub-group of 45 patients who underwent clinically indicated invasive coronary angiography (ICA), the application of SSF was associated with a significant increase of accuracy of CCTA (93% vs. 76%; p=.019).

More recently, several studies highlighted the benefits of combining whole heart coverage, single-beat scanner, and SSF, especially for patients with high heart rate or atrial fibrillation [22-27]. In 2023, the CONVERGE Registry [27], a multicenter registry at four centers, evaluated the image quality in 104 patients with heart rate above 70 beats per minute using CT scanners with coverage of 16 or 4 cm. Out of the 104 patients, 52 underwent scans using the 4 cm scanner and 52 underwent scans using the 16 cm scanner. The mean heart rate was similar in both groups (75 ± 7 bpm; p = 0.426). SSF was used for correcting motion artifacts. The data showed that, overall, there were far fewer poor- or fair-quality images in the 16 cm arm of the study (5/52 = 9.6%) than in the 4 cm scanner arm (38/52 = 73%), with the majority of artifacts comprising stepwise and RCA motion artifacts.

4. SnapShot Freeze 2: 3D-Motion Correction to Further Compensate for Coronary Motion and Beyond

Recently GE HealthCare introduced the latest iteration of this technology, SnapShot Freeze 2 (SSF2), which incorporates motion correction for the entire heart, beyond just the coronary arteries.

As with the first generation of the motion correction algorithm, SSF2 uses the information from adjacent cardiac phases, available from a single rotation, to characterize motion at the prescribed target phase. In addition to the coronary vessels, the second generation technology extends motion correction to the whole heart. Leveraging the power of conjugate pairs of partial angle reconstruction images for motion estimation and motion compensation, in a fully automated fashion, SSF2 searches each region of the image volume for a local motion path that is consistent with the subset of measured data that passes through that portion of the image volume. Once the motion path is known, the data is deconstructed into a series of subsets according to the time at which the corresponding projection rays were measured. Each image volume in the series is then spatially deformed by the motion field that maps the motion state from the respective time to the central reference time given by the prescribed cardiac phase. As whole heart correction requires motion characterization along all three axes, this also provides greater robustness in coronary motion correction itself, a notion especially helpful for extreme motion scenarios and motion paths predominantly along the z-axis (Figure 4).

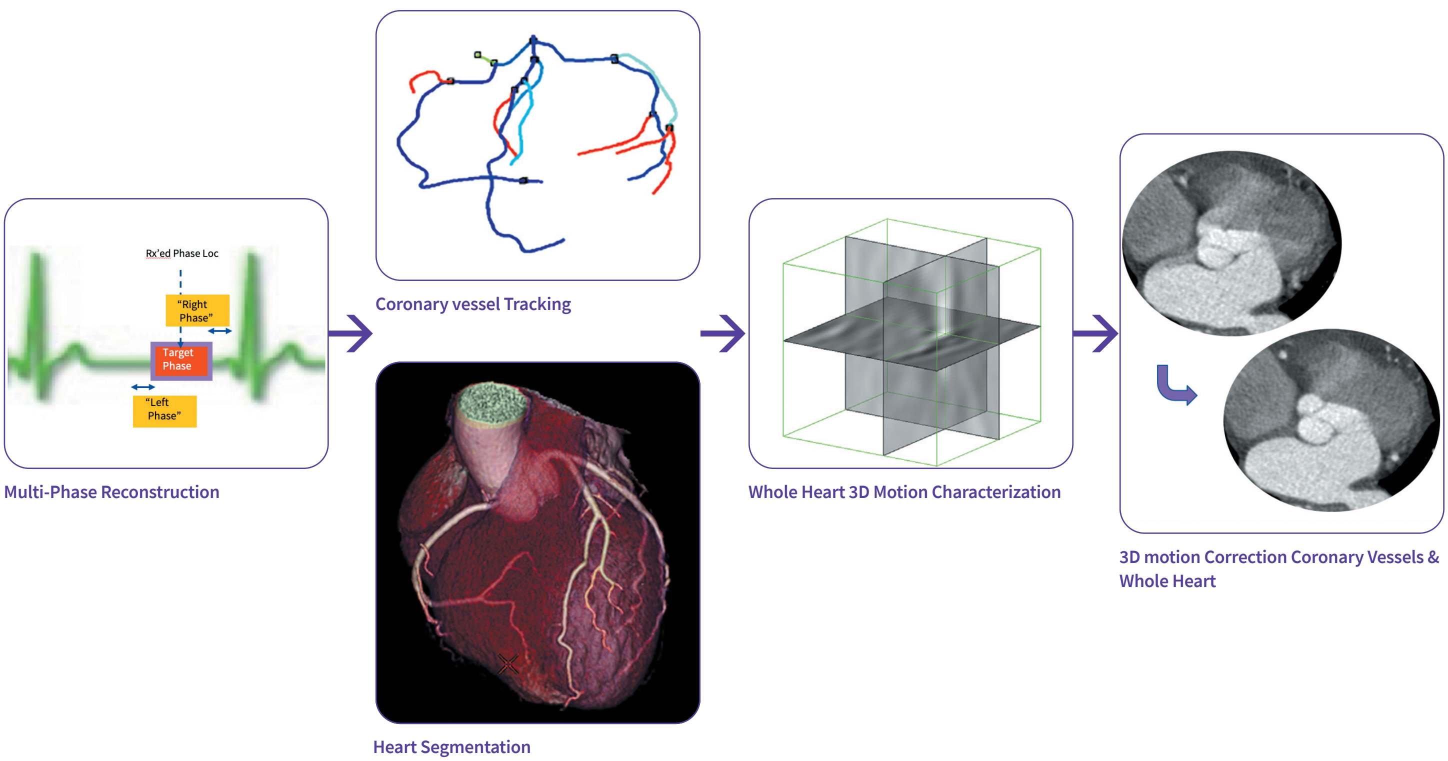
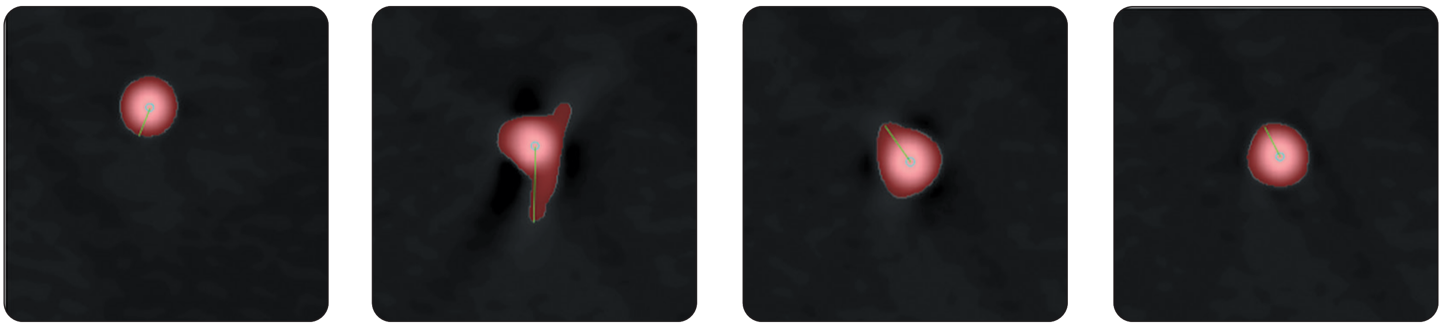


Figure 4: Both the path and the velocity of the vessel and the whole heart are characterized, in order to determine the actual vessel and cardiac structure position at the prescribed target phase. SnapShot Freeze 2 adaptively compensates for any residual motion at that phase, effectively compressing the reconstruction window by a factor of 6.

While initially targeted for the Revolution CT and Revolution Apex scanners with full-organ coverage in a single rotation, SSF2 is designed to be fully compatible with GE HealthCare scanners utilizing an 80mm or 40mm detector configuration, including axial step-and-shoot (Snapshot Pulse), fast switch dual energy (GSI Cardiac), and cardiac helical acquisitions.

To assess SSF2 motion correction performance, a motion phantom study similar to SSF detailed earlier was conducted utilizing a myocardial phantom with attached iodine-based contrast filled tubular vessels modeling the coronaries imaged at average velocity levels of 10, 17, 33, 53, and 65 mm/s with 0.23s/rotation cardiac axial acquisition. The radial FWTM metric was again utilized to quantify the magnitude of motion artifact versus the static reference. Vessel motion blur, Motion $Blur_{vel}$ = $FWTM_{vel}$ – FWTMstatic, was assessed for the different vessel velocities (Figures 5, 6 and 7).



Static 3 mm tube | **Moving 3 mm tube** | **Moving 3 mm tube + SSF** | **Moving 3 mm tube + SSF2.0**

Figure 5: Tube measurement example demonstrating the impact of motion and of SnapShot Freeze 1 and 2. Pixel values > 10% of the max are color coded red for a 2D visualization of the Radial FWTM metric utilized for calculation of Motion $Blur_{32.5mm/s}$.

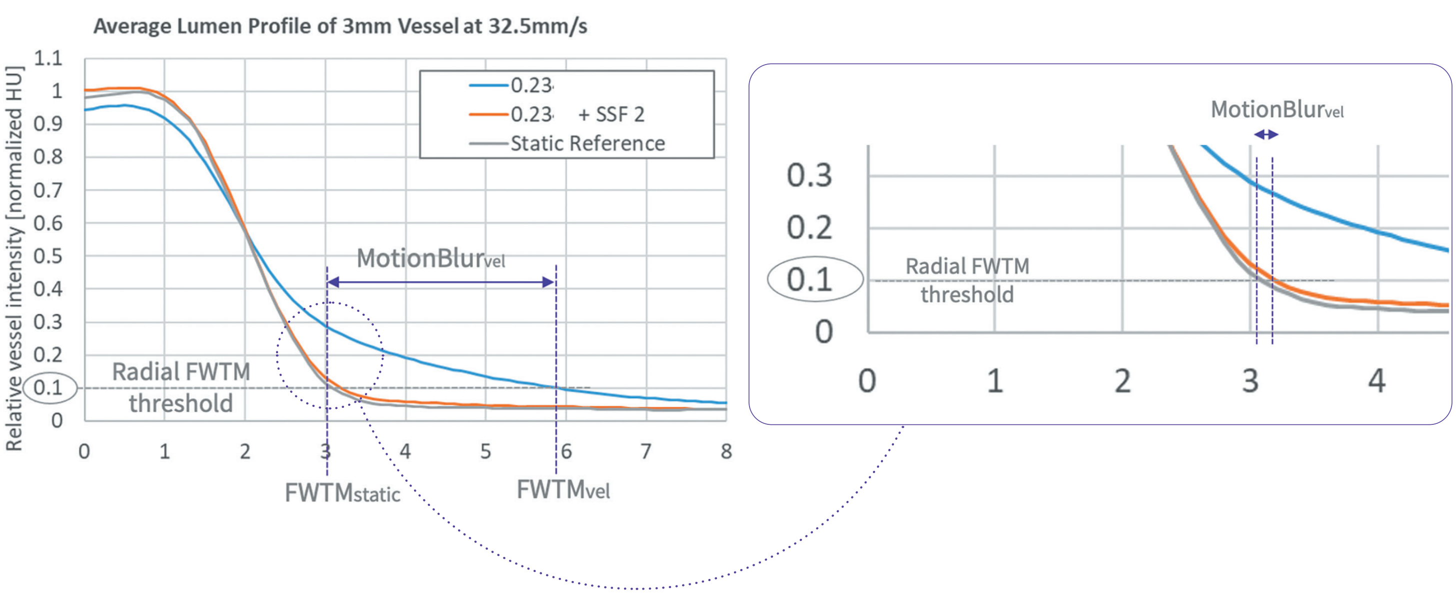
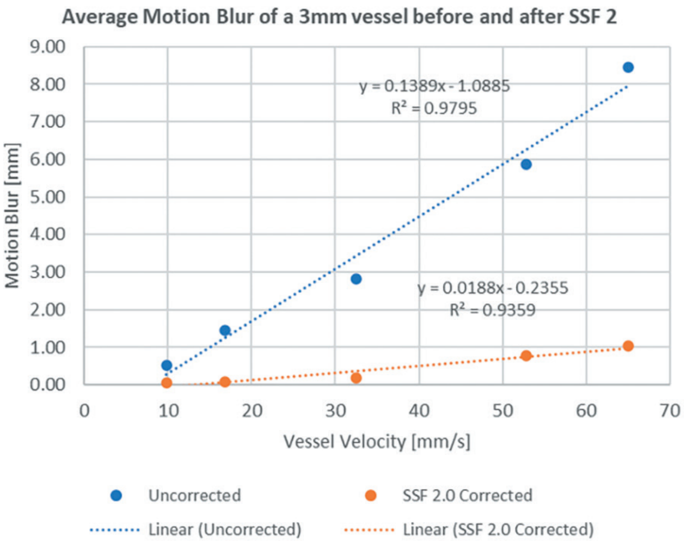


Figure 6: 3 mm vessel radial profiles. 0.23s/rot with SnapShot Freeze 2 corrected vs. 0.23s/rot gantry speed and static reference. The radial FWTMs of 0.23s+SSF2 is very close to the corresponding static reference. FWTM, full-width, tenth-max.



Motion Blur vs. Vessel Velocity			
	Uncorrected	SSF2 Corrected	
Average Velocity (mm/s)	Motion Blur (mm)	Motion Blur (mm)	Motion Reduction Factor
65	8.46	1.05	8.1
52.8	5.86	0.77	7.6
32.5	2.83	0.18	15.7
16.8	1.45	0.09	16.1
9.8	0.53	0.05	10.6

Figure 7: Motion Blurring for a 3 mm vessel from 9.8-65 mm/s showing a motion reduction factor ranging from 7.6 to 16.1.

As a complement to the mechanical phantom study, a mathematical 4D phantom was also utilized. Vessels of 2, 3, and 4 mm diameter, within a water background and following a profile similar to that of the physical phantom experiment were used. This allowed us to compare the image quality of SSF2 motion corrected vessels at a nominal gantry speed versus images acquired at a much higher simulated gantry speed.

Simulation runs were acquired at various gantry start angles to generate multiple raw CT acquisition datasets that could then be processed by standard reconstruction and SSF2. Results for a 35 mm/s vessel velocity with a 0 degree start angle, acquired with simulated gantry periods of 0.23s and 39ms, are shown in Figure 8.

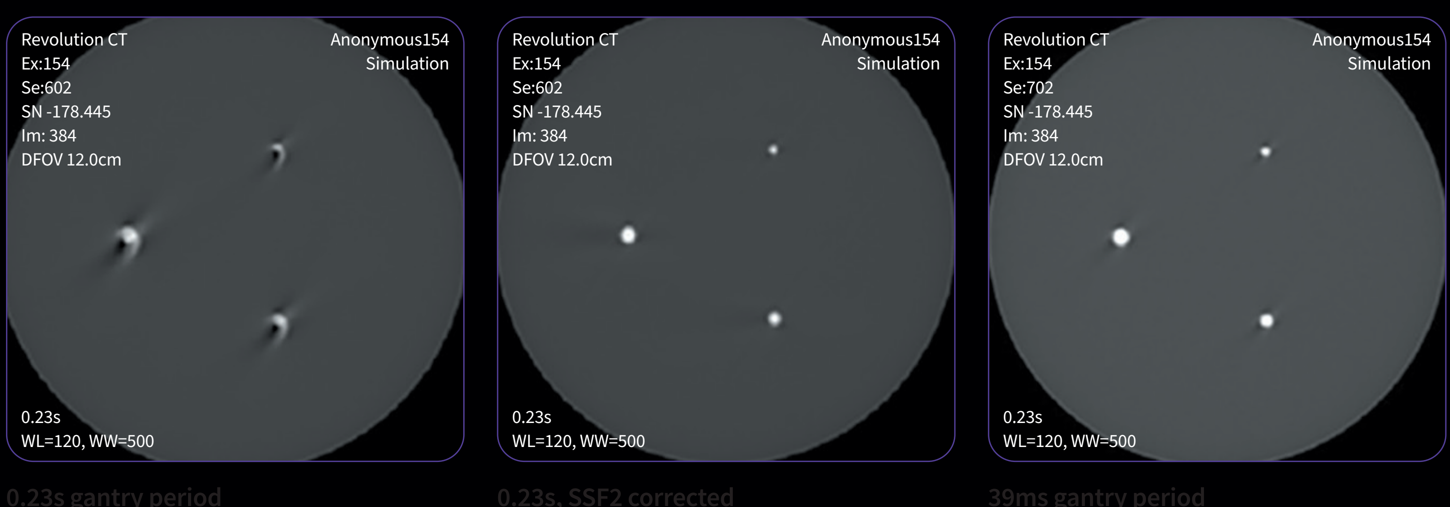


Figure 8: Evaluation of SSF2 images generated from a mathematical phantom with a simulated 0.23s/rot acquisition vs. native images generated from the same phantom with 6x faster simulated acquisition (0.039s/rot) - SSF2 images are visually comparable to those made with a 6x faster gantry speed.

In conclusion

Snapshot Freeze 2, in conjunction with **0.35 sec/rotation gantry speed,** provides a reduction in coronary motion artifacts that is comparable to a 0.058s/rotation equivalent gantry rotation speed with effective temporal resolution of **29 msec.***

Snapshot Freeze 2, in conjunction with **0.28 sec/rotation gantry speed,** provides a reduction in coronary motion artifacts that is equivalent to a 0.047s/rotation equivalent gantry rotation speed with effective temporal resolution of **24 msec.****

Snapshot Freeze 2, in conjunction with **0.23 sec/rotation gantry speed,** provides a reduction in coronary motion artifacts that is equivalent to a 0.039s/rotation equivalent gantry rotation speed with effective temporal resolution of **19.5 msec.*****

*As demonstrated in mechanical and mathematical cardiac phantom testing.
** As demonstrated in phantom testing using a commercially available motion phantom and also with a mathematical cardiac phantom with linear motion of variable velocity. The 0.047 s/rotation images are modeled without application of Snapshot Freeze 2. Results may vary in clinical applications.
***As demonstrated in phantom testing using a commercially available motion phantom and also with a mathematical cardiac phantom with linear motion of variable velocity. The 0.039 s/rotation images are modeled without application of SnapShot Freeze 2. Results may vary in clinical applications.

5. Benefits with SnapShot Freeze 2

SSF2 is an intelligent motion correction algorithm designed for automated whole heart motion correction, providing:

- Coronary motion correction;
- Valve motion correction;
- Chamber, myocardium motion correction;
- Great vessel motion correction.

Several clinical studies have demonstrated the benefits of SSF2, not only for coronary imaging but also for valve and prosthetic valve imaging, as well as for pediatric cardiac imaging [28-36].

a. Benefits of SnapShot Freeze 2 in coronary imaging

Liang et al. assessed SSF2 in comparison to its previous version in 81 patients with increased heart rate who underwent CCTA and ICA (mean age : 58.7 ± 9.8 years; mean heart rate: 83.8 ± 8.9 bpm; heart rate variability: 10.2 ± 4.8 bpm; mean effective dose: 1.0 mSv) [28].

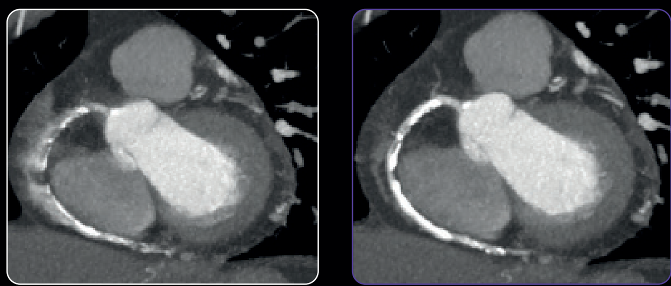
Images reconstructed without motion correction, with SSF, or with SSF2 were rated by two independent cardiovascular radiologists on a 4-point grading scale (1 = non-diagnostic image quality, 2 = adequate image quality, 3 = good image quality, and 4 = excellent image quality; coronary segments with an image quality score ≥ 2 were considered interpretable).

SSF2 significantly improved image quality scores relative to no motion correction and to SSF, respectively, (3.56 ± 0.63 vs. 2.81 ± 0.85 vs. 3.21 ± 0.79; both p< .001) and interpretability on a per-segment level (99.2% vs. 92.5% vs. 97.2%, respectively), per-vessel level (98.5% vs. 81.2% vs. 92.6%, respectively), and a per-patient level (95.1% vs. 56.8% vs. 77.8%, respectively). SSF2 also significantly improved the diagnostic performance of CCTA (assessed by two independent interventional radiologist using ICA as the reference standard) relative to no motion correction and to SSF, respectively, for the detection of significant stenosis on the per-segment (area under the curve [AUC] = 0.95 vs. 0.81 vs. 0.86, respectively; both p<.001), the per-vessel (AUC = 0.97 vs. 0.81 vs. 0.88, respectively; p<.001) and the per-patient level (AUC = 0.91 vs. 0.31 vs. 0.75, respectively; p<.001). Liang et al. hence concluded that SSF2 significantly improved image quality and diagnostic accuracy of one beat CCTA in patients with increased heart rate.

A second comparison between SSF2, SSF and no motion correction algorithm was conducted by Yamaguchi et al [29]. The assessment of the image from 50 patients (mean age: 74 ± 10 years; mean heart rate: 61.2 ± 12.0 bpm) performed by two independent radiologists who rated the delineation of coronary arteries on a 5-point Likert scale (from 1 = non-diagnostic to 5 = excellent) highlighted a significant increase of the median scores on per-vessel level when using SSF2 compared to SSF and no motion correction algorithm for the right coronary, the left anterior descending and the left circumflex arteries (5.0 vs 4.5 vs 3.0, 5.0 vs 4.5 vs 3.8 and 5.0 vs 4.5 vs 4.0 respectively; all p<.05). On a per-segment level, the delineation scores were also improved for both observers when using SSF2 compared to SSF for segments 1, 2, 8, 9, 10, 12 and 13 (all p < .05). All segments were rated as interpretable (score ≥3) by both observers when SSF2 was used while averages of 2.3% and 8.8% of the segments were considered as non-interpretable when applying SSF or no motion correction algorithm, respectively.

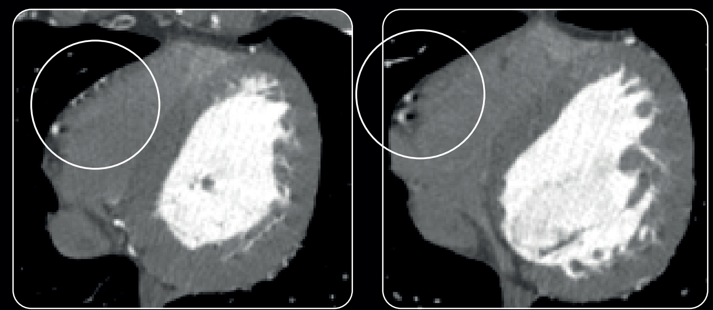
Consequently, Yamaguchi et al. stated that SSF2 improved the delineation and interpretability of coronary arteries in CCTA compared to SSF.

Benefits of SnapShot Freeze 2 in coronary imaging

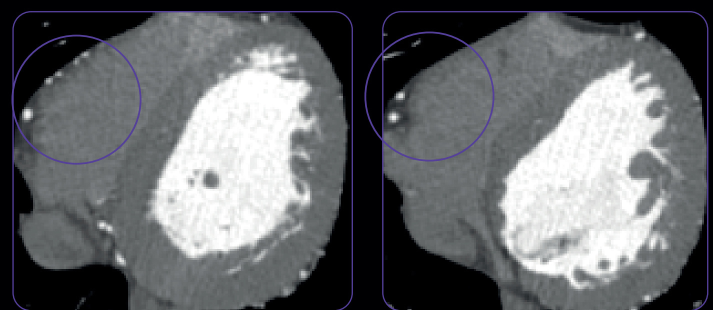


Without SnapShot Freeze 2 **With SnapShot Freeze 2**

Figure 9: 89 bpm example demonstrating motion correction of the right coronary artery.
Images Courtesy of Centre Hospitalier Emile Roux – Limeil-Brévannes, France

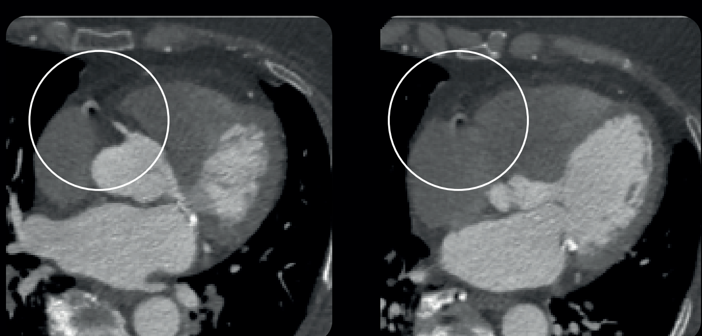


Without SnapShot Freeze 2

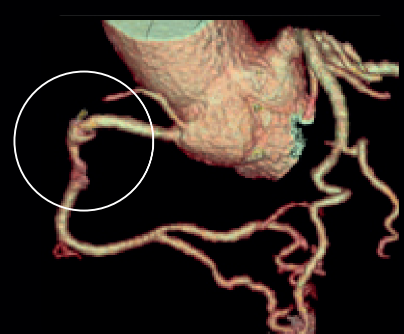


With SnapShot Freeze 2

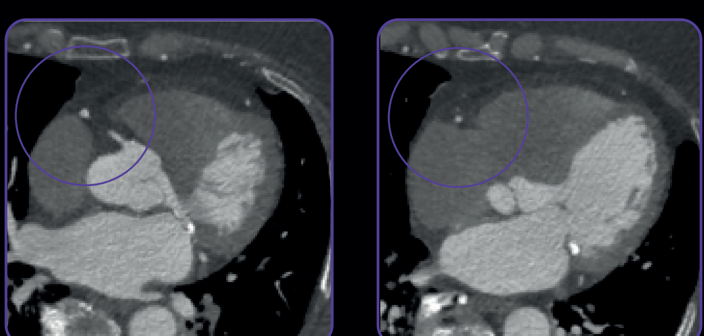
Figure 10: 73 bpm example demonstrating motion correction of the right coronary artery visualized on axial images.
Images Courtesy of Pr. Serfaty, CHU Nantes Laennec, France



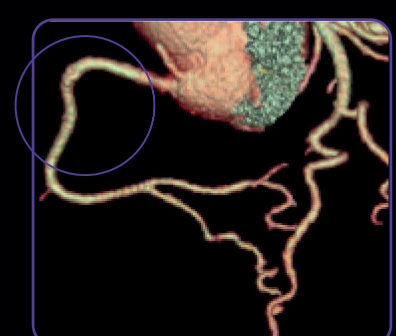
SnapShot Freeze 1



SnapShot Freeze 1



SnapShot Freeze 2



SnapShot Freeze 2

Figure 11: This example demonstrates how SSF2 further corrects coronary motion compared to SSF1

b. Benefits of SnapShot Freeze 2 in valve imaging – Pre-TAVI procedure

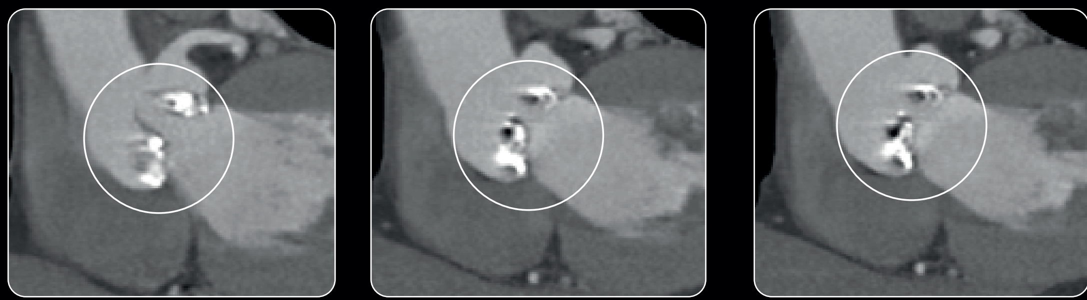
Matsumoto et al. applied SSF2 to cardiac CT images that were acquired before transcatheter aortic valve implantation (TAVI) in 90 patients with severe aortic stenosis; patients were divided into 3 groups of 30 patients each based on their heart rate (low: < 60 bpm; intermediate: 60–69 bpm, and high: ≥ 70 bpm) [30]. Systolic and diastolic phases were reconstructed without and with SSF2. A quantitative assessment of the images conducted by two radiological technologists revealed that the standard deviation of the aortic annulus area was significantly smaller in SSF2 reconstruction s of systolic and diastolic phases (R-R interval of 40 and 75%, respectively) than in standard ones at low (94.7 vs. 63.3 and 105.2 vs. 78.9)-, intermediate (71.8 vs. 47.9 and 90.4 vs. 58.3)-, and high heart rate (58.7 vs. 45.1 and 70.3 vs. 45.8 all: $p < 0.05$). The qualitative image quality assessed by two radiological technologists using a 5-point Likert scale (1 = very poor; 2 = poor; 3 = fair; 4 = good; and 5 = excellent) was significantly improved when using SSF2 in the systolic phase of patients with low and intermediate heart rates compared to standard images (3.6 vs. 2.6 and 3.5 vs 2.1 respectively; both p<.001) and in both phases of patients with high heart rates (3.7 vs. 2.5 and 3.2 vs 2.2 respectively; both p<.001).

Matsumoto et al. concluded that their findings suggested that SSF2 algorithm was superior to standard reconstruction because it improved the image quality and reduced motion artifacts especially in patients with a high heart rate or a 40% R-R interval. SSF2 may contribute to improving the measurement accuracy of the aortic annulus prior to TAVI.

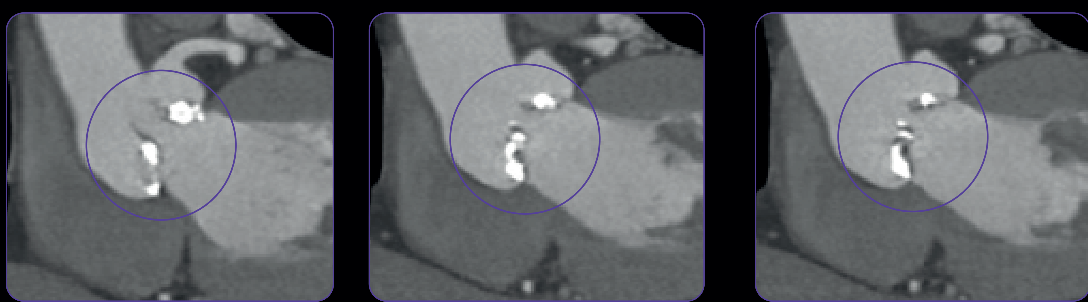
Benefits of SSF2 in pre-TAVI imaging were also observed in a prospective study led by Zhang et al. on 64 consecutive TAVI candidates (mean age: 73.4 ± 6.7 years; mean heart rate: 74.2 ± 18.2 bpm; heart rate variability: 13.4 ± 16.9 bpm) [31]. The comparison of data from 20%, 30%, 40%, and 75% of the R-R interval reconstructed with and without SSF2 demonstrated that the motion correction algorithm significantly improved subjective image quality of aortic valves and coronary arteries at all phases (p<.001). It increased the rate of aortic valves judged as interpretable (Likert score ≥3 on a 5-point scale) in the 20 and 30% R-R intervals (100% with SSF2 vs. 41.7% without, and 100% with SSF2 vs 76.6% without respectively; both p<.001) and judged as excellent (Likert score ≥4 on a 5-point scale) at all phases of the cardiac cycle (p<.001). Similarly, the rate of coronary arteries of interpretable and excellent image quality increased in each phase (p<.001). This led to an increase of the accuracy in the detection of >50% stenoses in the 30% phases images at per-patient, per-vessel and per-segment levels (85.1% with SSF2 vs 59.6% without, 94.2% with SSF2 vs 75% without and 98.4% with SSF2 vs 80.6% without respectively).

These results led Zhang et al. to conclude that SSF2 enabled the accurate measurement for aortic valve and satisfactory diagnostic performance for coronary arteries stenosis in the same systolic phase for TAVI planning.

Benefits of SnapShot Freeze 2 in valve imaging

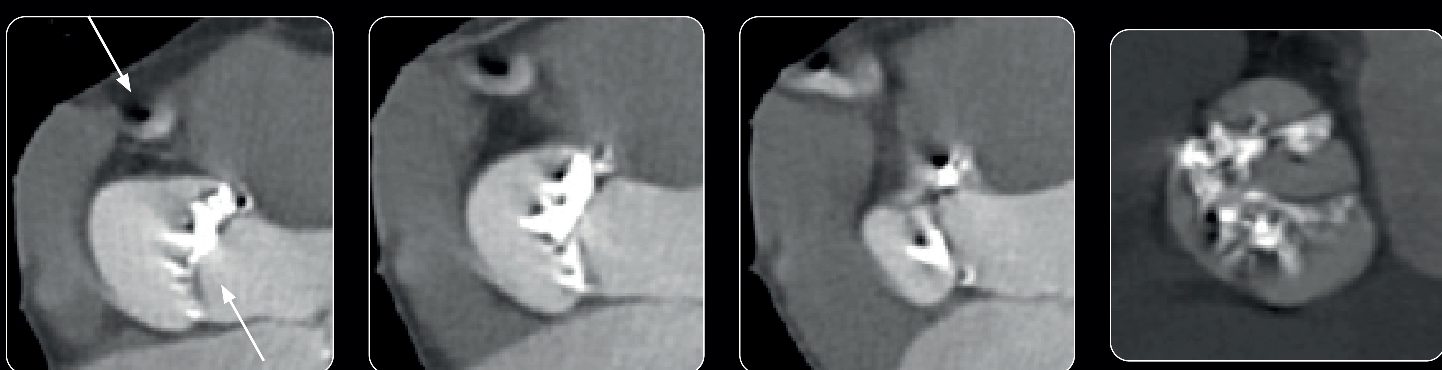


Without SnapShot Freeze 2

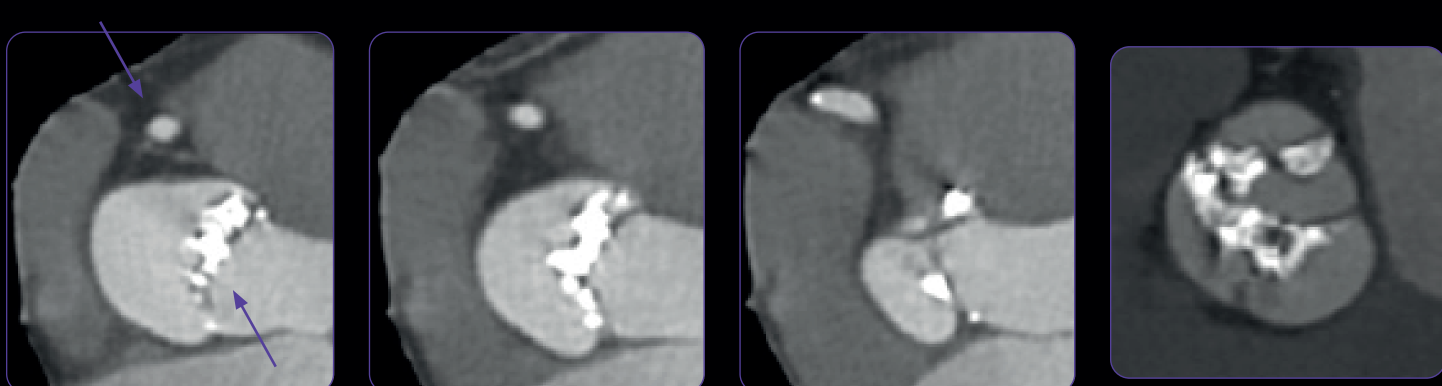


With SnapShot Freeze 2

Figure 12: This example demonstrates how SSF2 improved aortic valve visualization. Images Courtesy of Pr. Serfaty, CHU Nantes Laennec, France



Without SnapShot Freeze 2



With SnapShot Freeze 2

Figure 13: SSF2 improves both coronary and aortic valve visualization. Images Courtesy of Pr. Serfaty, CHU Nantes Laennec, France

c. Benefits of SnapShot Freeze 2 in prosthetic valve imaging

Suh et al. included 20 patients (8 male; mean age: 23.0 ± 2.1 years; mean heart rate: 64.9 ± 14.3 bpm; heart rate variability: 34.5 ± 24.1 bpm) who had a mechanical valve replacement and were referred for a control cardiac CT, to evaluate the impact of SSF2 on image quality and detection of prosthetic valve abnormalities [32]. Raw data from every 10% of the R-R interval were identified, reconstructed with and without the motion correction algorithm, and assessed by two observers for both valvular and subvalvular regions of the valve on a 4-point scale (1 = poor visualization, 2 = fair visualization, 3 = good visualization, and 4 = excellent visualization; phases with a score ≥3 were considered diagnostic quality). The application of SSF2 yielded better mean image quality scores compared to no motion correction, respectively, for both valvular and subvalvular regions (3.54 ± 0.29 vs. 3.11 ± 0.48 and 3.51 ± 0.41 vs. 2.97 ± 0.52 ; both p <.0001) and increased the number of phases with diagnostic image quality for both regions (p <.0001). All of the 32 valves assessed were defined as diagnostic for the detection of abnormalities when using SSF2, while 6 were classified as non-diagnostic without the motion correction algorithm. For detection of prosthetic valve abnormalities, especially subprosthetic pannus, images reconstructed with SSF2 had a larger area under the receiver operating characteristic curve (1 vs. 0.85 without motion correction; p=.0043). Suh et al. concluded that, compared to standard images, SSF2 could improve the image quality and decrease motion artifacts in CT scans of mechanical valves and may lead to enhanced detection of prosthetic valve abnormalities.

d. Benefits of SnapShot Freeze 2 in pediatric cardiac imaging

Two pediatric studies also compared images reconstructed with SSF2 and SSF. The first study, led by Sun et al., included 42 consecutive pediatric patients (median age: 8 months; range: 5 days to 6 years) with high heart rates (mean heart rate: 122.6 ± 18.8 bpm; heart rate variability: 6.98 ± 5.98 bpm) and directly compared the image reconstruction outcomes of SSF2 and its predecessor [33]. A subjective evaluation of image quality using a 4-point grading scale and involving two independent cardiovascular radiologists revealed that SSF2 improved the interpretability of the origin of the right coronary artery (97.6% vs. 81.0%; p<.01) and the left coronary artery (100% vs. 88.1%; p<.01). SSF2 also offered a significantly better image quality for the aortic, pulmonary, and tricuspid valves (p<.01, p=.04, and p =.01, respectively) compared to SSF. For ventricle septum and atrial septum, there was no statistical difference in image quality.

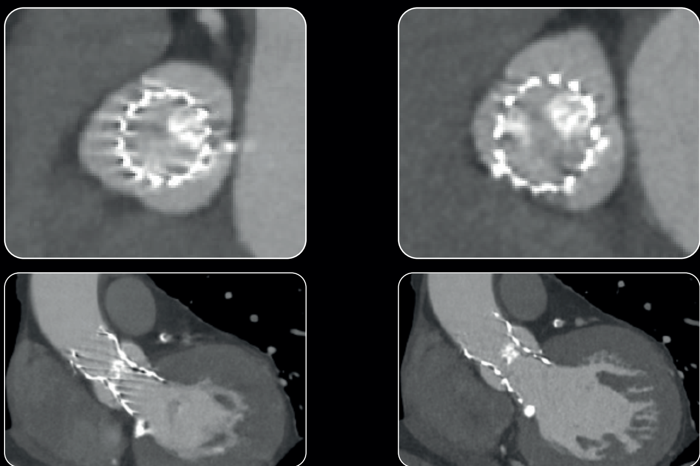
The second study in pediatric cardiac imaging was conducted by Le Roy et al. who investigated the benefits of SSF2 applied to monophasic reconstruction in comparison to both SSF and multiphasic reconstruction from 47 CCTA exams of pediatric patients (mean age: 5.5 ± 4.7 years; mean heart rate: 95 ± 27 bpm) [34]. The evaluation of 16 segments of the coronary tree, left and right ostia, ascending aorta, pulmonary artery, aortic valve, and cardiac chambers by two independent radiologists (using a 4-point semi-quantitative scale) revealed that SSF2 provided better results than its previous generation or regular monophasic reconstructions in terms of interpretability rates (99.3% vs. 94.3% and 92.1% respectively; p<.001) and proportion of structures with optimal quality (90.1% vs. 68.2% and 60.3% respectively; p<0.001). While SSF2 applied on monophasic reconstruction provided similar interpretability rates to multiphasic acquisitions (99.3% vs. 99.6%, p=.5), SSF2 images had a higher proportion of structures with optimal quality (90.1% vs. 81.1%, p<.001).

Based on these results, Le Roy et al. concluded that SSF2 in a single retrospectively processed cardiac phase offered similar interpretability than multiple phases acquisitions and could be adopted to reduce children exposure to radiation.

Benefits of SSF2 in prosthetic valve imaging

Without SnapShot Freeze 2
45% of R-R

With SnapShot Freeze 2
45% of R-R



With SnapShot Freeze 2
75% of R-R

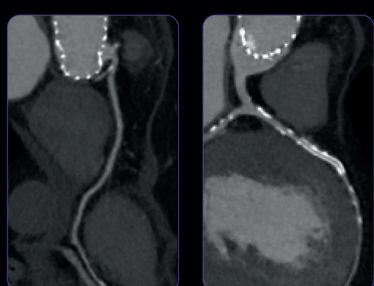


Figure 14: SSF2 improves both coronary and prosthetic valve visualization.
Image courtesy of Derriford Hospital – Plymouth Hospitals NHS Trust

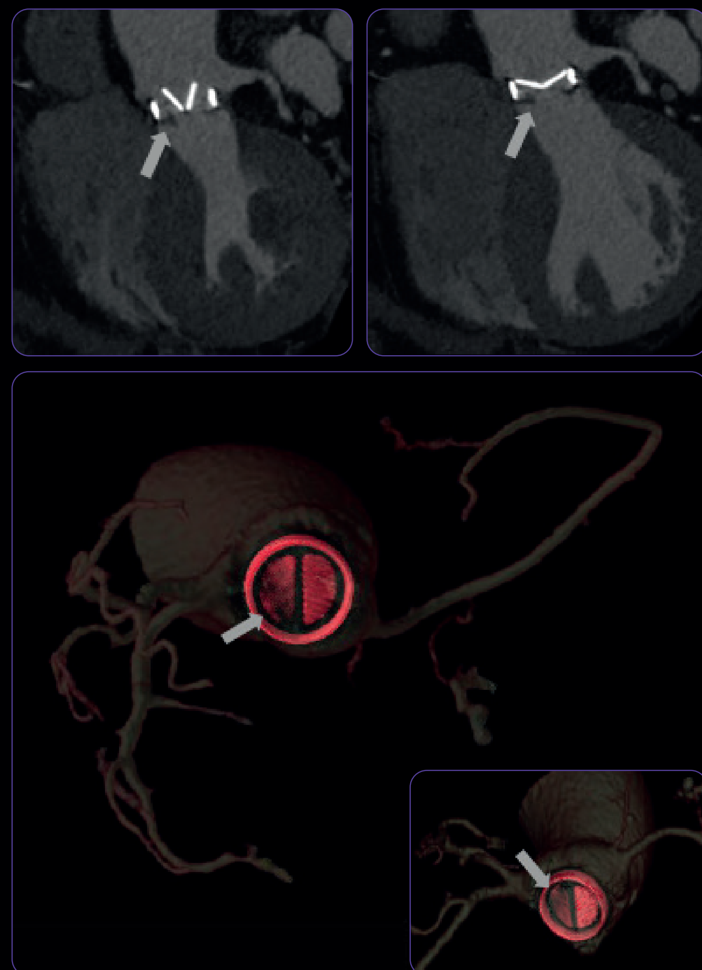
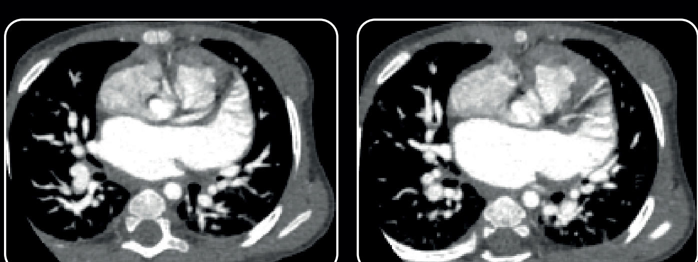
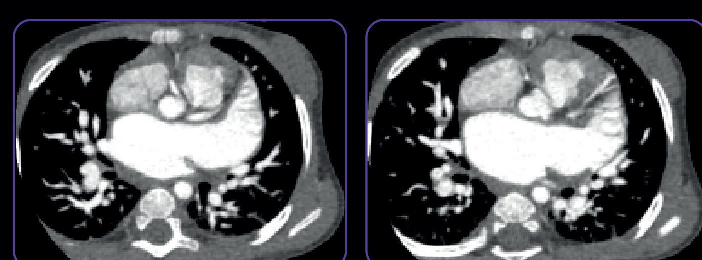


Figure 15: This example demonstrates clear depiction of opening and closing of the prosthetic valve.
Image courtesy of CHU Laennec – Nantes - France

Benefits of SSF2 in pediatric cardiac imaging



Without SnapShot Freeze 2



With SnapShot Freeze 2

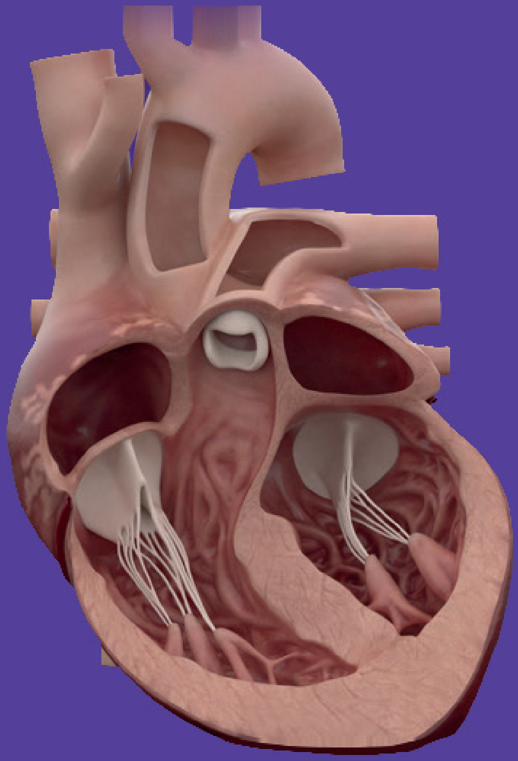
Figure 16: This example demonstrates the benefits of SSF2 in pediatric imaging (8-month, 128 bpm)

6. Summary of SnapShot Freeze 2 clinical studies

Clinical Indications	Population	Cohort size	Mean Heart Rate (bpm)	Image Quality improvement with SSF2	Benefits with SSF2	Ref.
CCTA	Adult	81	83.8 ± 8.9	+27% increase of overall subjective quality score per-segment with SSF2 vs no motion correction (3.56 ± 0.63 vs. 2.81 ± 0.85; p< .001)	Increased image interpretability on per-segment level: 99.2% with SSF2 vs. 92.5% with no motion correction; p<.001 Improved diagnostic accuracy for detection of significant stenosis on per-segment level: 96.8% with SSF2 vs. 81.5% with no motion correction; p<.001	[28]
	Adult	50	61.2 ± 12.0	Significant increase of the median scores on per-vessel level when using SSF2 compared to SSF1 and no motion correction algorithm for the right coronary, the left anterior descending and the left circumflex arteries (5.0 vs 4.5 vs 3.0, 5.0 vs 4.5 vs 3.8 and 5.0 vs 4.5 vs 4.0 respectively; all p<.05)	All segments were rated as interpretable (score ≥3) by both observers when SSF2 was used while averages of 2.3% and 8.8% of the segments in average were considered as non-interpretable when applying SSF1 or no motion correction algorithm respectively.	[29]
Pre-TAVR aortic annulus evaluation	Adult	90	64 (range 34–119)	Improvement of 38% and 67% of subjective image quality in systolic phase of patients with low and intermediate heart rates respectively, with SSF2 vs no motion correction (3.6 vs. 2.6 and 3.5 vs 2.1; both p<.001). Improvement of 48% and 45% of subjective image quality in systolic and diastolic phases of patients with high heart rates, with SSF2 vs no motion correction (3.7 vs. 2.5 and 3.2 vs 2.2; both p<.001).	Dispersion of sizing: Average decrease of the standard deviation of the aortic annulus area by 31% compared to standard reconstruction at systolic and diastolic phases of low, (94.7 vs. 63.3 and 105.2 vs. 78.9), intermediate (71.8 vs. 47.9 and 90.4 vs.58.3), and high heart rates respectively (58.7 vs. 45.1 and 70.3 vs. 45.8)	[30]
	Adult	64	74.2 ± 18.2 bpm	It increased the rate of aortic valve judged as interpretable (Likert score ≥3 on a 5-point scale) in the 20 and 30% R-R intervals (100% with SSF2 vs. 41.7% without, and 100% with SSF2 vs 76.6% without respectively; both p<.001) and judged as excellent (Likert score ≥4 on a 5-point scale) at all phases of the cardiac cycle (p<.001)	The rate of coronary arteries of interpretable and excellent image quality increased in each phase (p<.001). This led to an increase of the accuracy in the detection of >50% stenoses in the 30% phases images at per-patient, per-vessel and per-segment levels (85.1% with SSF2 vs 59.6% without, 94.2% with SSF2 vs 75% without and 98.4% with SSF2 vs 80.6% without respectively)	[31]
Mechanical valve prosthesis abnormalities	Adult	20	64.9 ± 14.3	Increase of 14% and 18% of subjective image quality for valvular and subvalvular regions with SSF2 vs. no motion correction (3.54 ± 0.29 vs. 3.11 ± 0.48 and 3.51 ± 0.41 vs. 2.97 respectively; p <.0001)	Larger area under the curve of the receiver operating characteristic curve for detection of detection of subprosthetic pannus: 1 vs. 0.85 without motion correction; p=.0043	[32]
Congenital heart disease	Pediatric	42	122.6 ± 18.8	Significantly better subjective image quality for the aortic, pulmonary, and tricuspid valves with SSF2 compared to SSF spacing/odd new line here (p<.01, p=.04 and p =.01 respectively)	Improved interpretability of the origin of the right and the left coronaries: 97.6% with SSF2 vs. 81% with SSF1 and 100% with SSF2 vs. 88.1% with SSF1 respectively; both p<.01	[33]
CCTA	Pediatric	47	95 ± 27	Higher proportion of structures with optimal quality with SSF2 compared to SSF or regular monophasic reconstructions : 90.1% versus 68.2% and 60.3%, respectively, all p<.001)	Improved interpretability rate of the coronary tree, left and right ostia, ascending aorta, pulmonary artery, aortic valve, and cardiac chambers compared to SSF or standard monophasic acquisitions : 99.3% versus 94.3% and 92.1%, respectively, all p<.001.	[34]

7. Conclusion

Over the last decade, cardiac CT technologies have substantially improved and expanded, thereby significantly enhancing image quality and diagnostic accuracy. The utilization of second-generation whole-heart motion correction algorithms, such as SSF2, has improved the visualization of coronary arteries. Additionally, SSF2 allows clear imaging for structures such as the aortic annulus, which may be useful for pre-procedure assessments for transcatheter aortic valve implantation, and prosthetic valves. These advances continue to optimize cardiac imaging modalities by minimizing motion-related artifacts.



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