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Fourier Analysis of STimulated echoes (FAST) for the quantitative analysis of left ventricular twist

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Abstract

Purpose—To validate a novel method for the rapid and facile quantification of left ventricular (LV) twist from tagged magnetic resonance images and demonstrate the potential clinical utility in a series of 20 healthy volunteers.

Materials and Methods—Cardiac MRI short-axis images were acquired with tissue tagging in twenty healthy subjects and six canines. The tagged images were processed using a novel Fourier Analysis of the STimulated echoes (FAST) method, which uses a series of Fourier-space operations to measure LV twist with limited user interaction. A subset of eight healthy subjects and the canine data were compared to results from previously validated “gold standard” software (FindTags). Interobserver and intraobserver coefficients of variation (CV_{INTER} and CV_{INTRA}), linear regression, and Bland-Altman analyses were used to assess agreement between observers and methods.

Results— CV_{INTRA} for peak systolic twist (2.9% and 2.6%) and CV_{INTER} (4.3% and 4.2%) were all small. Linear regression analysis of the FAST and FindTags twist values indicated very good agreement in healthy subjects ($R=0.91$) and in canines ($R=0.95$). Bland-Altman comparison of the FAST and FindTags twist results indicated excellent agreement in healthy subjects (bias of 0.02° , 95% confidence intervals (-3.7° , 3.7°)) and canines (bias of 0.2° , 95% confidence intervals (-2.7° , 3.1°)). Peak systolic twist in healthy subjects averaged $10.5 \pm 1.9^\circ$ degrees.

Conclusion—The FAST method for quantifying LV twist produces results that are not significantly different from the current “gold standard” in a fraction of the user interaction time and has demonstrated feasibility in human subjects.

Keywords

Tagging; Twist; Image Processing; Left Ventricle

INTRODUCTION

Alterations in left ventricular (LV) twist are important in many pathophysiologies including myocardial infarction (1), dilated cardiomyopathy (2), mitral regurgitation (3), diastolic

dysfunction (4) and aging (5). LV twist is a measure of the rotation of the apex relative to the base of the heart. Herein, we exploit the fact that object rotation in image space directly corresponds to a rotation in Fourier space. When spatial modulation of magnetization (SPAMM) tagging is employed, stimulated echoes form dominant features in magnitude Fourier space. With appropriate image processing, quantitation of the rotation of the stimulated echoes about the center of Fourier space corresponds to a rotation of the LV SPAMM tags. We have developed and validated a quantitative method termed Fourier Analysis of Stimulated echoes (FAST) that requires limited user interaction for the quantitative analysis of LV twist. This study validates a novel method for the rapid quantification of left ventricular twist from tagged magnetic resonance images, evaluates the intra- and interobserver variability in the assessment of twist in six canine studies and eight healthy human subjects. We also demonstrate the utility of the FAST method in a series of twelve additional healthy human subjects

MATERIALS AND METHODS

Animal Protocol

The animal protocol was approved by the institution's animal care and use committee and adhered to guidelines set forth by the National Institutes of Health. Six beagles were anesthetized with a 0.1ml intramuscular injection of Acepromazine and then 2.5% solution of Sodium Pentothal at 1ml/2.3kg intravenously. The animals were then placed on positive pressure ventilation with 1.5% isoflurane for the duration of the scan. Animals were fitted with a right atrial-pacing electrode using fluoroscopic guidance. The pacing electrode was used for both sensing cardiac rhythm or for pacing.

Canine MRI Protocol

Imaging was performed using a General Electric 1.5T CV/i scanner (GE Healthcare, Waukesha, WI, US) and a 4 element phased array knee coil. Short axis stripe tagged images were acquired using a modified 3D fast gradient echo pulse sequence with the following parameters: 180mm×180mm×128–160mm field of view, 384×128×32 acquisition matrix, 12° imaging flip angle, ±62.5kHz bandwidth, TE/TR=3.4/8.0ms, 5 pixel (2.3mm) tag spacing, and 4 or 5mm slice thickness. The sequence was also modified to include segmented multiphase imaging, combined respiratory and cardiac gating, and 1-3-3-1 spatial modulation of magnetization (SPAMM) tagging. Further modifications implemented a spatial frequency dependent number of views per segment (VPS) in order to reduce the acquisition time by a factor of 3.2 (6). Briefly, the highest phase-encoded spatial frequencies were acquired using VPS=8 and lower spatial frequencies were acquired with VPS=4 and VPS=2. The lowest spatial frequencies were acquired with VPS=1. Fifty-eight to sixty cardiac phases were reconstructed per slice, depending upon the heart rate.

In order to image for extended durations a reliable and robust respiratory gating technique was implemented. The respiratory pressure waveform was sampled at the proximal end of the endotracheal tube using the scanner's bellows transducer. The respiratory signal from the bellows transducer was then sampled by the pulse sequence throughout the scan to determine periods of minimal respiratory induced cardiac motion during end-expiration. The use of right atrial pacing provided the ability to phase lock the respiratory and cardiac motion to further minimize motion artifacts and also provided the ability to start the imaging sequence prior to systolic contraction in order to image the complete extent of systolic contraction.

The canine data was also incorporated, in part, because of its availability and relevance to basic science research for which tagging techniques have broad applicability. The canine

data was used in this study as part of the validation of the FAST method and to perform inter- and intra-observer analysis.

Healthy Subjects MRI Protocol

The local institutional review board approved this study and all subjects provided written informed consent. Eight (5 male, mean age of 37.0 years $\pm$ 17.0 years, weight 68.4 $\pm$ 16.9 kg, height 1.7 $\pm$ 0.2 m, heart rate 58.2 $\pm$ 10.8 beats/min) healthy human subjects with no history of cardiovascular or respiratory disease were studied for comparison with FindTags. Additionally, twelve (10 male, 2 female, mean age of 26.4 years $\pm$ 4.3 years, weight 80.8 $\pm$ 20.3 kg, height 1.8 $\pm$ 0.1 m, heart rate 74.5 $\pm$ 11.8 beats/min) healthy human subjects with no history of cardiovascular or respiratory disease were studied using only FAST.

An Avanto 1.5T scanner (Siemens Healthcare, Erlangen, Germany) and a six element body matrix coil in combination with a six element spine matrix coil were used, while the subjects rested in a head first supine position. All image were acquired with ECG triggering while the volunteer held his or her breath at end-expiration. Scout images were obtained in the axial, coronal, and sagittal orientations, which were then used to plan the study. A steady-state free precession cine sequence in parallel short-axis planes was used to select slices for acquisition of tagged images and subsequent twist measurements. The two short axis slices consisted of an apical slice and a basal slice selected based on the following criteria respectively: the most apical slice containing the presence of the blood pool throughout the entire cardiac cycle and the most basal slice in which the LV myocardium maintained a continuous annular shape during the entire cardiac cycle. Twist was calculated as the difference in the angle of rotation for matching frames between the apical and basal slices.

The same modified 1-1 SPAMM line tag sequence and the unmodified Siemens 1-3-5-3-1 SPAMM line tag sequence were used to acquire short-axis images in healthy volunteers (n=8) at the base and apex of the LV with the following parameters: 360-300 $\times$ 300-280mm FOV, 5-6mm slice thickness, 192 $\times$ 144 acquisition matrix, 15° imaging flip angle, 501 Hz/pixel receiver bandwidth, TE/TR = 3.5-3.7/4.7-6.5 ms, 7-8 VPS, 2 averages, and 14-16 cardiac phases. Cine images were acquired for both horizontally and vertically tagged images with a 10mm tag spacing for both apical and basal slices. The average breath hold time was 23.8 seconds.

A cardiac spoiled gradient echo MRI pulse sequence was modified to support 1-1 SPAMM line tags and used to acquire short-axis images in healthy volunteers (n=12) at the base and apex of the LV with the following parameters: 300 $\times$ 300mm FOV, 5mm slice thickness, 192 $\times$ 96 acquisition matrix, 15° imaging flip angle, 250 Hz/pixel receiver bandwidth, TE/TR = 5.2-5.4/9.15ms, 4 VPS, and 18-24 cardiac phases. Cine images were acquired for both horizontally and vertically tagged images with an 8mm tag spacing for both apical and basal slices. The average breath hold time was 28.7 seconds.

Tag Tracking

Tissue tags in two short axis slices were tracked semi-automatically using the FindTags (7) software, which we define as “gold standard” results. FindTags was used as our gold standard because the software was readily available. Harmonic phase (HARP) imaging analysis is an alternative commercially available FDA approved software package (Diagnosoft, Cary, North Carolina, USA) that is commonly used to calculate twist (8). The “gold standard” estimates of LV rotation at basal and apical slice levels for the duration of trackable tag persistence were obtained from the rotation of horizontal and vertical tag intersections about the LV centroid determined using FindTags.

FindTags requires binomially weighted (e.g. 1-3-3-1 or 1-3-5-3-1) tagged images to accurately track tag intersections. Note, these 1-3-5-3-1 SPAMM tagged images were not available for the second healthy subjects (n=12) population. The data from this second group of healthy subjects was used as further evidence of the capabilities of the FAST method. 1-3-3-1 SPAMM data was used during the FindTags analysis of canine twist and 1-3-5-3-1 SPAMM was used during the analysis of twist in normal subjects due to the availability of data. This subtle difference in tag generation is not expected to impact the results.

Fourier Analysis of STimulated echoes (FAST)

The only user interaction required for FAST LV twist analysis is contouring of the LV epicardium in an end-systolic frame at the basal and apical slice level (Figure 1). The epicardial contour was used for least squares fitting of an ellipse to the LV epicardial boundary. The long and short axes of the ellipse were used to define the location of 90% attenuation of the 2D fourth-order Butterworth mask and the orientation (rotation) of the fit ellipse was used to rotate the 2D Butterworth mask. Masking was necessary to define the region of interest (i.e. LV myocardium), thereby eliminating tissues that did not rotate from further analysis. Butterworth filters also reduce ringing subsequent to 2D Fourier transformation, Figure 1C. The same mask is applied to each subsequent frame in the same dataset. The epicardial contour displaces <1 pixel throughout the cardiac cycle, therefore the individual epicardial contours on each frame are largely the same. The endocardial border displaces much more, but due to the lack of tag coherence in the blood pool a mask is not needed. Subsequent to masking, the image was 2D Fourier transformed and the center peak (free induction decay, FID) in the Fourier image was nulled with a circular mask to reduce the interference of the high FID signal intensities (low spatial frequency) during the detection of object rotation Figure 1D. Next, the image was cropped (depending on the direction of phase encoding) so that only the central 64 lines of k-space (-32 to +32) remained, which reduced the matrix size and subsequent processing time, Figure 1E.

The Fourier magnitude data for each frame was 2D cross-correlated with a bi-cubic interpolated, rotated (step-size of 0.1°) version of the frame immediately after it within the same slice. The maximum of the two-dimensional cross-correlation from all tested rotations defined the angle of rotation between those frames. The cumulative angle of rotation for each frame is equal to the sum of the angles of rotation from the frames before it plus the current cross correlation angle of rotation for the frame. This process was repeated for all frames in the basal and apical slices. The angle of rotation computed from the horizontal and vertical tags was averaged within matching time frames for both the apical and basal slices. Twist was calculated as the difference in the angle of rotation for matching frames between the apical and basal slices. Peak twist was defined as the maximum twist value for each subject. Matlab R2007a (The MathWorks, Inc., Natick, MA, USA) was used for all processing on a MacBook Pro (Apple, Cupertino, CA, USA) with a 2.4 GHz Intel Core 2 Duo processor. 1-1 SPAMM was used during the FAST analysis of twist in normal subjects and 1-3-3-1 SPAMM data was used during the FAST analysis of canine twist due to the availability of data. 1-1 SPAMM images were used for FAST analysis because it was expected that the image intensity and distribution of the dominant Fourier space features (stimulated echoes) would be more accurately detected by cross correlation (see Discussion).

Statistical Analysis

Intra- and inter-observer analysis was performed for the canine studies, wherein the left ventricular epicardium and endocardium at end systole were each contoured twice by two investigators. Each trial consisted of contouring basal and apical slices for each of the six canine studies. For each trial, the mean and standard deviation of peak systolic twist were

calculated and compared. The intra-observer coefficient of variation, CV_{INTRA} , was calculated for each investigator as the standard deviation of the peak systolic twist from both trials times 100 divided by its mean. The inter-observer coefficient of variation, CV_{INTER} , was calculated for each trial as the standard deviation of the mean difference between observers in peak systolic twist times 100 divided by its mean. Linear regression analysis of twist values (six canine studies, each comprised of 40 analyzable cardiac phases) from the two investigators against the FindTags results was performed by calculation of Pearson's correlation coefficient (R). Peak systolic twist for all canine trial combinations (e.g. Observer #1-Trial #1 vs. Observer #2-Trial #2) was compared using the Wilcoxon signed-rank test for paired non-parametric samples. The paired t-test was used to compare the canine twist values from each trial with the FindTags twist values of each cardiac phase. P-values less than 0.05 were considered significant. Bland-Altman analysis is used to compare two measurement techniques (9). A Bland-Altman analysis for the first two-thirds of the cardiac cycle (before tag rotation becomes undetectable by either method) was performed to compare all of the canine FAST twist data collected by both investigators to that of the FindTags data.

Additionally, linear regression analysis of healthy subject twist ($n=8$) for the first 500 ms of the cardiac cycle (before tag rotation becomes undetectable by either method) derived from the FAST method and FindTags was performed by calculation of Pearson's correlation coefficient (R). Peak systolic twist for healthy subjects was compared using the Wilcoxon signed-rank test for paired nonparametric samples. The paired t-test was used to compare healthy subject ($n=8$) twist values for the first 500ms of the cardiac cycle from the FAST method with the FindTags twist values of each cardiac phase. A Bland-Altman analysis for the first 500ms of the cardiac cycle was performed to compare healthy subject ($n=8$) FAST twist data collected to FindTags data.

RESULTS

Validation in Canines

The mean peak systolic twist for Investigator 1 was $10.3^{\circ} \pm 2.2^{\circ}$ and $10.1^{\circ} \pm 2.5^{\circ}$ (Trial #1 and #2 respectively). The mean peak systolic twist for Investigator 2 was $10.4^{\circ} \pm 2.6^{\circ}$ and $10.2^{\circ} \pm 2.5^{\circ}$ (Trial #1 and #2 respectively). Mean peak twist derived using FindTags was $11.4^{\circ} \pm 2.7^{\circ}$. CV_{INTRA} for peak systolic twist for Investigator 1 and 2 were 2.9% and 2.6% respectively. CV_{INTER} for peak systolic twist for Trial #1 and #2 were 4.3% and 4.2% respectively. The mean difference in peak systolic twist for Trial #1 and Trial #2 were $-0.15^{\circ} \pm 0.4^{\circ}$ and $-0.13^{\circ} \pm 0.4^{\circ}$ respectively. Linear regression analysis of FAST twist values from the two investigators (960 data points) and the FindTags results yielded a Pearson's correlation coefficient of $R=0.95$ and the equation $\text{FAST}=0.9\text{FindTags}+0.8$ (Figure 3B). Linear regression analysis of Investigator 1 and Investigator 2 yielded a Pearson's correlation coefficient of $R=0.99$ and the equation $y=1.0x-0.05$. The Wilcoxon signed-rank test did not reveal any significant differences between the peak systolic twist for any combination of trials. No significant differences were detected by the paired t-test for FAST twist values from each trial compared to the FindTags twist values in each cardiac phase. Figure 2, compares the FAST twist and FindTags results (mean $\pm$ SD) for six canine studies and demonstrates good agreement between the two methods.

Bland-Altman analysis for the first two-thirds of the cardiac cycle compares all of the FAST twist data collected by both investigators to the FindTags data (Figure 3). There is excellent agreement between FAST and FindTags for calculating LV twist with a bias (FAST-FindTags) of 0.2° and 95% confidence intervals of $(-2.7^{\circ}, 3.1^{\circ})$. Intra-observer Bland-Altman analysis for the first two thirds of the cardiac cycle for Investigator 1 and 2 yields a bias of 0.1° and 0.1° and a 95% confidence interval of $(-0.3^{\circ}, 0.5^{\circ})$ and $(-0.3^{\circ}, 0.5^{\circ})$

respectively. Inter-observer Bland-Altman analysis for the first two thirds of the cardiac cycle for Investigator 1 and 2, Trial 1 compared to Trial 1 and Trial 2 compared to Trial 2, yields a bias of 0.1° and a 95% confidence interval of $(-0.5^\circ, 0.4^\circ)$.

The average user interaction time for the FAST method was 2.6 ± 0.3 minutes; this time includes study selection and contouring of the epicardium and endocardium for the basal and apical slices for both horizontal and vertical tags. Since the tags deform in both the horizontal and vertical directions both sets of tags are needed to properly quantify LV twist. User interaction times for the FindTags data were not available, but typically average 30–60 seconds per image. The average computational time for the FAST algorithm was a total of 37 minutes for the horizontal and vertical tags at the basal and apical slice level (4 separate sets of images containing 40 frames each with a matrix size of 256×64).

Validation in Healthy Subjects

Linear regression analysis in healthy subjects ($n=8$) for the first 500 ms of the cardiac cycle with FAST twist values and FindTags results yielded a Pearson's correlation coefficient of $R=0.91$ and the equation $\text{FAST}=0.9\text{FindTags}$, (Figure 5B). The Wilcoxon signed-rank test of the same data did not reveal any significant differences between the peak systolic twist for any combination of trials. No significant differences were detected by the paired t-test for FAST twist values compared to the FindTags twist values in each cardiac phase. Figure 4, compares the FAST twist and FindTags results (mean $\pm$ SD) for eight healthy subjects and demonstrates good agreement between the two methods. Peak systolic twist and early diastolic untwisting are clearly visible in all cases (Figure 4). Figure 4 shows incomplete untwisting because the tags have faded too much for quantitative analysis. Bland-Altman analysis for the first 500 ms of the cardiac cycle compares the FAST twist data to the FindTags data (Figure 5). There is excellent agreement between FAST and FindTags for calculating LV twist with a bias (FAST-FindTags) of -0.5° and 95% confidence intervals of $(-4.3^\circ, 3.4^\circ)$. Mean peak twist derived from the FAST method ($n=8$) was $11.5^\circ \pm 2.3^\circ$ and $12.6^\circ \pm 1.6^\circ$ using FindTags. The mean peak LV twist from all of the healthy volunteers ($n=20$) using FAST was $10.5 \pm 1.9^\circ$ with an average user interaction time of 2.7 ± 0.4 minutes and an average post processing time of approximately 21 minutes.

DISCUSSION

In the present study, we evaluated the performance of the FAST method as compared with FindTags for the quantification of LV twist. The FAST algorithm for quantifying LV twist is a fast, reliable, and reproducible method. Furthermore, the quantitative results from FAST LV twist analysis compare very favorably (no statistical differences, negligible bias) with the FindTags ("gold standard") results and the user analysis times were short (<3 minutes per study). Inter- and intra-observer agreement of the FAST method for measuring LV twist was very good.

The FAST method incorporates four important techniques: a 2D Butterworth mask, FID suppression, matrix cropping, and 2D cross-correlation. The primary function of the 2D Butterworth mask is to isolate the rotating myocardial tissue and suppress stationary tissue. Without the use of this mask, the FAST method would return twist values based on the entire tagged cardiac MR image including the chest wall. The currently implemented FAST algorithm is relatively insensitive to the precise 2D Butterworth filter used, so long as the stationary tissues are sufficiently suppressed.

The Butterworth filter is used in the spatial domain to reduce ringing artifacts after transformation to the Fourier domain. Subsequently a circular mask is applied directly in Fourier space to null the FID. This array is not transformed back to the spatial domain,

therefore ringing is not an issue and the difference between using a circular filter and a Butterworth filter with a few pixel roll-off are likely negligible.

FID suppression was used to minimize the effects of the highest intensity low spatial frequencies, which can interfere with estimates of object rotation. Bland-Altman analysis of the FAST method without FID suppression and FindTags for one trial had a bias of 0.13° and a CI $(-2.7, 3.0)$, which indicates that FID suppression may not be necessary. An alternative strategy for minimizing the FID is CSPAMM (10) which effectively nulls the FID due subtraction of the two complementary tagging patterns. Lastly, the Fourier space matrix is cropped to the central 64-lines in the phase-encode direction after FID suppression in order to reduce image processing time (14.8 times faster than processing times using original size images of 256×256). Cropping along this dimension reduces the spatial frequency content along the tag's length and has a negligible effect on the quantitative results. Bland-Altman analysis of FAST without cropping and FindTags for one trial had a bias of 0.22° and a CI $(-2.6, 3.1)$. This bias is better than that of the cropped FAST method, but not significantly different. Nevertheless, the time savings gained from cropping the matrix makes up for it.

Strong correlation and agreement of twist measurements between FAST and FindTags were found in the present study. Compared to FindTags, for which the user interaction time requires many tens of minutes, the FAST processing significantly reduces both user interaction time and the analysis time and produces comparable results. The computational processing time of the FAST method, despite running automatically after initial contour selection, is a current limitation. Methods that will reduce the processing times include using a faster computer, a better optimization algorithm, a measure of image similarity between each rotated frame that is faster to compute than cross-correlation, and a transform to polar coordinates for direct rotation estimates.

The FAST method yields robust measurements of LV twist, with strong inter- and intra-observer agreement. The mean LV peak systolic twist for each investigator and each trial were not significantly different indicating excellent user agreement and highly reproducible analysis. The mean peak systolic twist values from the healthy human subjects were in good agreement with previously reported value of $10.4^\circ \pm 2.6^\circ$ (11), which apical and basal slice selection criteria similar to the criteria used in this study. However, there is a range of literature values reported for LV twist in healthy human subjects (12). Differences in the value between the mean peak LV twist value reported in this study and that reported across the range of studies in the literature may result from the slice selection criteria and differences in the subject population. In addition to having good agreement with mean peak twist literature values, the measurements from both investigators matched well with the FindTags ("gold standard") values.

With regards to the variability within each measure, we note that the selected slices are 5–6mm thick with approximately 10cm between the apical and basal slices. The slice position may be different between volunteers by approximately half a slice (2.5–3.0mm) from the desired anatomic slice locations as described in the Methods section, which may account for a $\sim 0.5^\circ$ degree of rotation, or 5% of the variability. Reproducibility studies or simulations are needed to appropriately address the other sources of variability in the peak twist measurement. Importantly, FAST and FindTags do not appear to have significantly different variability, which leads us to conclude that intra-subject variability may be the largest component of the variability.

The FAST method performs well with 5mm slices, which also helps reduce intra-slice shear effects. For thick slices, a within slice shear may reduce the sensitivity for measuring

rotations with the FAST method, effectively smearing the stimulated echo and stimulated anti-echo and reducing the rotation measurement. If the short-axis prescription is tilted relative to the LV long-axis, then errors may be introduced in the twist measurements. The incorrect short axis prescription may result in an inter-slice heterogeneity in rotation as a consequence of the projection of LV rotation onto a plane whose normal is skew to the axis of LV rotation. The FAST method may have a more difficult time detecting rotation as the stimulated echo and stimulated anti-echo will be smeared. This may be an inherent limitation of the FAST method when compared to FindTags. FindTags should not be limited in detecting tag intersections despite the skewed axis and as a result should accurately estimate the rotation of the imperfect short-axis slice.

The healthy human data was acquired using 1-1 SPAMM tagging. The primary reason for the use of 1-1 SPAMM tagging over the product provided sequence (1-3-5-3-1 SPAMM) was due to the image intensity and distribution of the dominant Fourier space features (stimulated echoes and free-induction decay, FID) in the Fourier transformed tagged image. The stimulated echoes arise as a consequence of tag generation. In the case of 1-1 SPAMM tagging the majority of the image intensity is distributed between two stimulated echoes and the FID, whereas in the product sequence the image intensity is distributed across six stimulated echoes and the FID. As the tags fade later in the cardiac cycle, the Fourier transformed images suffer a loss of contrast to noise ratio as a direct result of the lack of tag detectability. Thus, 2D cross correlation is less effective later in the cardiac cycle. The use of 1-1 SPAMM tagging allows the stimulated echo intensities to remain higher than that of background noise for a longer duration of the cardiac cycle compared to the product provided sequence and may improve quantitative estimates of LV twist. Future improvements in the tagging sequence (13–15) may improve quantification of LV untwisting during diastole, thereby further extending the utility of the FAST method.

The FAST method for calculating LV rotation is based on a comparison of temporally adjacent frames and the total rotation arises from the summation of inter-frame rotations, but inter-frame errors can also arise from this process. One alternative to determining angle of rotation would be to compare only the first frame with each subsequent frame. One problem with this approach is the significant change in tag orientation and contrast from the first frame to last frame. In this case error may arise due to the large changes between images. Furthermore, a different search algorithm would need to account for a wider range of possible rotations. It is also important to note that the current implementation of the FAST method is designed to calculate global LV twist, unlike HARP, FindTags, or DENSE (16), which can compute regional differences in twist and strain. For cardiac diseases with significant within slice rotational heterogeneity, the stimulated echo and stimulated anti-echo may smear enough to make accurate estimates of global rotation difficult.

The optimal imaging strategy for efficiently acquiring MRI data amenable to the fast and accurate analysis of LV twist remain the subject of ongoing investigation. The optimal strategy will likely reflect a balance of Fourier peak amplitudes relative to the noise levels in Fourier space, breath hold limitations, FID nulling strategies (filters versus CSPAMM), line tags versus grid tags and parallel imaging. The FAST method for quantifying LV twist produces quantitative results that are equivalent to the current “gold standard” in a fraction of the user interaction time and has demonstrated applicability in human subjects. While user interaction time is under 3 minutes, full automation of this technique is a necessity for clinical acceptance.

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Figure 1.

The FAST method is used to estimate left ventricular (LV) rotations from conventional SPAMM tagged images (A). The image is first manually contoured (B) and segmented with a two-dimensional Butterworth filter matched to the contours (C) to isolate the LV myocardium. The segmented image is then Fourier transformed (D) and the free induction decay is nulled (E), before cropping (F). The final step of the FAST algorithm involves 2D cross-correlation with another cardiac phase in order to estimate the LV rotation.

Figure 2.

The mean LV twist from 6 different canines is plotted as a function of percent cardiac cycle for both FindTags (“gold standard”) and the FAST method. Error bars indicate ± 1 standard deviation. No statistically significant differences between the techniques were observed, which indicates FAST is a suitable alternative to FindTags analysis.

FAST versus FindTags in Canines

Figure 3.

(A) Bland-Altman analysis of canine LV twist for each investigator using the FAST method is compared to the FindTags (“gold standard”) results indicates excellent agreement between the two methods with a bias of 0.2° and a variance of $(-2.7^\circ, 3.1^\circ)$. (B) Linear Regression analysis of canine LV twist for both investigators using the FAST method is compared to FindTags and results in the equation $FAST=0.9FindTags+0.8$ ($R=0.95$).

Mean Left Ventricular Twist in Healthy Subjects

Figure 4.

LV twist in 8 healthy subjects is plotted above as a function of frame number for the first 500 ms of the cardiac cycle for both the FAST method and FindTags the “gold standard”. Error bars indicate ± 1 standard deviation. Systolic twisting and early diastolic untwisting are both evident. The peak twist observed in these subjects is in good agreement with previously published results, indicating that the FAST method produces expected results with limited user interaction.

FAST versus FindTags in Healthy Subjects

Figure 5.

(A) Bland-Altman analysis of healthy subject LV twist using the FAST method is compared to FindTags (“gold standard”) results indicating excellent agreement between the two methods with a bias of -0.5° and a variance of $(-4.3^\circ, 3.4^\circ)$. (B) Linear regression analysis of healthy subject LV twist using the FAST method is compared to FindTags and results in the equation $\text{FAST} = 0.9 \times \text{FindTags}$ ($R = 0.91$).