Published in final edited form as:

Magn Reson Imaging. 2020 February ; 66: 193–198. doi:10.1016/j.mri.2019.08.033.

Quantitative Detection of Changes in Regional Wall Motion Using Real Time Strain-Encoded Cardiovascular Magnetic Resonance

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1. INTRODUCTION

A comprehensive cardiovascular magnetic resonance (CMR) exam includes assessment of regional wall motion, which typically involves qualitative interpretation by an experienced reader, although time-consuming quantitative measurements of myocardial wall thickening can be performed. Myocardial strain imaging offers the potential to more accurately quantify the extent and severity of regional wall motion abnormalities and has even been proposed as a mechanism to identify changes in regional contractility before they are visually evident¹. Strain imaging may be particularly valuable to assess the impact of coronary artery disease on the myocardium because ischemia is known to first alter the longitudinal deformation of the subendocardial myocardial fibers prior to impacting the regional thickening in the radial direction that is required to create a visually appreciable wall motion abnormality¹. In patients with chest pain, alterations in strain following the infusion of an inotrope such as dobutamine can be used to improve the detection of underlying coronary artery disease². Myocardial strain can be measured using several different CMR-based tagging techniques, such as complementary spatial modulation of magnetization (C-SPAMM)³ with harmonic phase encoding (HARP) post-processing^{4,5}, displacement encoding with stimulating echoes (DENSE)⁶, cine phase contrast imaging, and strain-encoded CMR (SENC)^{7–9}. Additionally, it is also possible to use feature tracking algorithms to derive strain measurements from standard cine-CMR images^{10,11}. Each of these approaches has its advantages and limitations. Recent improvements in SENC-CMR allow for image

acquisition to occur during a single heart beat in real time without sacrificing temporal resolution. Unlike the other strain imaging approaches, with SENC imaging being performed during a single heart beat, image quality is not significantly impacted by respiratory motion and arrhythmia. Previous single center studies have suggested that SENC-CMR can be used to improve the detection of coronary artery disease when compared to cine-image wall motion interpretation¹². In this multi-center study, we hypothesized that in the presence of coronary artery disease, changes in regional longitudinal and circumferential strain detected using SENC under intermediate-dose dobutamine stress CMR would precede changes in wall thickening visible on cine-CMR images.

2. METHODS

2.1 Patient Population

Twenty-nine patients with known or suspected coronary artery disease, who were scheduled for an invasive coronary angiogram, were prospectively recruited between June 2016 and May 2017 from 3 centers (University of Chicago, University of Bonn, and the German Heart Institute Berlin). Patients with a history of coronary artery bypass graft or evidence of myocardial infarction or left ventricular (LV) dysfunction were excluded. At each center, the respective institutional review board approved this study. All subjects provided informed consent for participation in this study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Clinical data were collected from each patient prior to CMR imaging.

2.2 Cardiac MR Protocol

An intermediate-dose dobutamine stress CMR protocol was matched across the participating three sites using a single vendor system across two software versions: Site 1 (1.5T Ingenia, Philips; V5.1.7) using a 32-channel array; Site 2 (3.0T Ingenia, Philips; V5.1.9) also with a 32-channel array; and Site 3 (1.5T Achieva, Philips; V5.1.7) using a 5-channel cardiac array. During resting conditions, cine-CMR images were acquired in the 2-, 3- and 4-chamber views, and in 3 short-axis slices at the apical, mid, and basal ventricular levels using a steady state free precession pulse sequence (TR=2.2–2.4ms; TE=1.1–1.2ms; FA=60° at 1.5T, FA=45° at 3.0T; 340×340mm², native 1–2mm × 1–2mm² interpolated to 0.65×0.65mm², slice thickness = 6 mm; sensitivity encoding (R=2), and temporal resolution <40ms). Next, SENC images were acquired in the same planes (TR=13ms; TE=0.7ms; FA=30°; 256×256mm²; native 4mm × 4mm² resolution interpolated to 1.0×1.0mm², slice thickness=10mm; with a 24ms SENC magnetization preparation prior to continuous acquisition of 40ms (3 spiral interleaves) per temporal frame over 1R-R cycle). After resting images were acquired, a dobutamine infusion was started and uptitrated to 20mcg/kg/min. Vital signs were collected serially during dobutamine infusion. After 3 minutes of dobutamine 20mcg/kg/min infusion (subsequently referred to as stress), an additional set of cine-CMR and SENC images was acquired in the above imaging planes. Figure 1 shows the schematics of the SENC-CMR technique. Figure 2 shows the intermediate-dose dobutamine

stress protocol employed in this study. Late gadolinium enhancement images were obtained 10–20 minutes after the injection of a gadolinium-based contrast agent at the discretion of the individual site.

2.3 CMR Analysis

CMR images were analyzed by a core-lab. Cine-CMR and SENC-CMR images were analyzed by separate investigators blinded to each other's measurements, coronary angiography findings, or other clinical factors. Cine-CMR images were assessed using commercial software (QMass 7.9, MEDIS Medical Imaging Systems, Leiden, The Netherlands). Using the basal, mid, and apical cine-CMR short-axis slices, regional wall thickness was measured at end-diastole and at end-systole during both resting and stress conditions. From these measurements, percent wall thickening (%WT) was calculated at rest and at stress for each of the 16 AHA segments.

SENC-CMR images were assessed using commercial software (MyoStrain v4.1, Myocardial Solutions Inc. Morrisville, NC). In brief, this software aligns the alternatively interleaved SENC frames obtained using high- and low-tuning, and uses the difference image between these frames in order to yield quantitative strain map. This commercially provided software approach reported the median strain measurement from the mid-third myocardial delineation. The 2-, 3-, and 4-chamber views of the SENC images acquired at rest and at stress were advanced to the end-systolic frame and an endocardial and epicardial boundary were manually traced. The contours were extrapolated into the other imaging frames and planes by the software. Once segmentation was completed, peak longitudinal strain (LS) and peak circumferential strain (CS) were derived from resting and stress images for each segment.

2.4 Coronary Angiography

Invasive X-ray angiography was performed using standard clinical techniques and interpreted by an interventional cardiologist blinded to all clinical and CMR data. Quantitative coronary angiography was used to categorize stenoses as either <50%, 50–75%, or >75%. All stenoses were then assigned to the appropriate downstream myocardial segments of a modified AHA 16-segment model.

2.5 Statistical Analysis

Continuous variables were reported as mean $\pm$ standard deviation or median (interquartile range) based upon normality determined by the Shapiro-Wilks test. The AHA segments were divided into 3 groups according to severity of coronary artery stenosis (<50%, 50–75% or >75%) affecting the artery supplying the segment. The mean %WT, LS, and CS were compared for each of the groups during resting and stress conditions, as well as the changes in each of the parameters from rest to stress were compared using clustered Wilcoxon signed-rank tests. Tests were two-tailed and considered statistically significant with a p-value <0.05. All statistical analyses were conducted using STATA MP version 15 (College Station, TX).

3. RESULTS

Patient characteristics, including baseline CMR and coronary angiography findings, are reported in Table 1. All CMR exams were successfully completed and all patients tolerated the exam well. The resting blood pressure and heart rate were 126 ± 19 mmHg / 71 ± 14 mmHg and 71 ± 12 beats per minute. At stress, they were 146 ± 22 mmHg / 72 ± 15 mmHg and 90 ± 30 beats per minute. %WT was successfully measured from cine-CMR images for all 464 segments (i.e. 29 patients $\times$ 16 segments). LS and CS SENC measurements were successfully determined in 94% of all of the segments.

Table 2 summarizes the wall thickening findings at rest and during stress in relation to the degree of stenosis as determined by coronary angiography. No statistically significant differences were observed between the groups of coronary stenosis severity at rest or during stress conditions. Additionally, no statistically significant differences in wall thickening was observed between resting and stress conditions for each subgroup of coronary stenosis.

Table 3 summarizes the SENC-based strain measurements at both rest and stress in relation to the degree of stenosis. During resting conditions, there was no difference in regional LS or CS between any of the coronary stenosis severity groups. Under stress conditions, LS was significantly decreased in segments supplied by arteries with $>75\%$ stenosis compared to those supplied by arteries with $50\text{--}75\%$ stenosis (medians -13.7% vs -17.3% , $p < 0.05$). However, there was no statistically significant difference in the CS between any of the subgroups during stress. When comparing resting to stress LS (i.e. change in strain), there was no significant increase in segments supplied by arteries with stenosis $0\text{--}50\%$ and $50\text{--}75\%$, but there was a trend towards worsening of LS from rest to stress in segments with $>75\%$ stenosis (medians, -16.0% to -13.7% , $p = 0.10$). Similarly, when comparing resting to stress CS, there was worsening in CS in segments with $>75\%$ stenosis (-17.9% to -16.7% , $p < 0.001$). Figure 3 shows SENC images from an individual with no coronary artery disease. Figure 4, show an individual with significant stenosis in the left anterior descending (LAD) artery, who did not have an appreciable wall motion abnormality on cine-CMR images at either resting or stress; however, an abnormality in CS was unmasked during stress conditions using SENC-CMR.

4. DISCUSSION

In this multi-center study, we investigated the utility of real-time SENC-CMR to quantify changes in regional longitudinal and circumferential strain in myocardial segments supplied by arteries with different degrees of coronary stenoses. We additionally investigated the value of SENC quantification of regional myocardial strain when compared to regional thickening measured using conventional cine-CMR images. Although there was no detectable change in regional wall thickening during resting or stress conditions associated with increasing severity of stenosis, there was a significant worsening in both LS and CS in segments supplied by arteries with severe stenosis that could be unmasked with the use of intermediate dose of dobutamine.

Despite the fact that CMR is considered the reference standard for the assessment of global left ventricular ejection fraction, the assessment of regional left ventricular function in clinical practice remains surprisingly qualitative. Based on visual assessment of cine-CMR images, regional wall motion is typically described as normal, hypokinetic, akinetic, or dyskinetic. A more quantitative approach to assess regional wall motion from cine-CMR images may be able to calculate percent wall thickening; however, making such measurements is time consuming if performed manually and is dependent on adequate delineation of the endocardial border at both end-diastole and end-systole. Although automated approaches to measure regional percent wall thickening do exist, they are also significantly limited by imprecise segmentation of the endocardial border. Accordingly, despite these limitations, a comparison against percent wall thickening was chosen in this study to allow an objective and quantifiable comparison between cine-CMR and SENC-CMR.

Another approach to quantifying regional ventricular function is through the evaluation of myocardial strain. Although there is an extensive body of literature describing the use of global strain measurements using both echocardiography and CMR, regional assessment of myocardial strain is less reliable due to lack of standardization and limited reproducibility^{13,14}. Myocardial strain can be measured using several different CMR techniques, such as feature tracking^{10,11}, C-SPAMM³, DENSE⁶, phase contrast imaging, and SENC⁷⁻⁹.

SENC employs a tagging excitation pulse in the in-plane direction parallel to the excited slice. The SENC pulse sequence applies a tuned tagging radiofrequency pulse within an excited slice thickness. Myocardial compression or decompression that occurs during the cardiac cycle is represented by a modulated signal intensity in the through-plane of the excited slice. The interleaving of two pre-defined modulation frequencies in consecutive cardiac phases allows for a sliding temporal window. Through-plane strain measurements are then derived by demodulating this parameter from each pair of consecutively cardiac phases. A particular strength of SENC-CMR is that image acquisition is completed within a single heart beat, which effectively makes it a real-time strain imaging technique. As a consequence, image quality is not significantly impacted by respiratory motion or arrhythmia and image acquisition does not prolong scan time in any meaningful way. Another strength of SENC-CMR is that quantification of the strain parameters does not require precise segmentation of the endocardial border which can be challenging and may significantly affect the accuracy of strain measurements made using other techniques, such as feature tracking.

The utility of prior iterations of SENC, acquired over the course of multiple heart beats, has been validated in several single center studies. The inter- and intra-observer variability of longitudinal and circumferential strain measurements made using SENC have been shown to be excellent, with an inter-class correlation ranging between 0.92 and 0.98¹⁵. It has been shown that global CS measured using SENC is significantly worse in patients with heart failure, when compared to healthy subjects and that correlates strongly with global CS measurements made using conventional myocardial tagging¹⁶. It has also been shown that SENC measurements of regional circumferential strain worsen as wall motion progresses from normal to hypokinesia to akinesia, validating its value for quantifying the severity of a

regional wall motion abnormality¹⁷. It has also been shown that regional CS measured using SENC worsens as the transmurality of a myocardial infarction increases. It is also worse within ischemic myocardial segments² and identifies ischemic segments better than either cine-CMR imaging or conventional myocardial tagging¹⁸. The use of SENC in the setting of dobutamine stress testing also has added prognostic value over clinical symptoms and conventional cine-CMR imaging¹⁹ and may even allow the detection of ischemia during infusion of lower doses of dobutamine¹².

In this study, we found that both regional LS and CS, measured using real-time SENC images acquired over a single heart beat, worsen in myocardial segments supplied by severely stenotic coronary arteries. These changes in regional strain occurred during the infusion of an intermediate dose of dobutamine despite the absence of any quantifiable change in regional wall thickening on cine-CMR images. Our study also suggests that real-time SENC imaging can be reliably performed at different medical centers. All prior studies examining the utility of SENC were single-center in nature; whereas the datasets used in our study were acquired at 3 separate international centers with no significant prior experience with the use of SENC.

4.1 Limitation

There are several limitations to this study. Although the real-time SENC technique used in this study is promising, further improvements in pulse sequence design may have the potential for additional improvements in the overall image quality. The pulse sequence utilized in this study acquired k-space data using a spiral sampling trajectory. While Cartesian sampling offers uniform and adequate k-space sampling of both central (i.e. low-frequency) and peripheral (i.e. high-frequency) domains, the variable density spiral acquisition used in this study yields a different k-space density²⁰, which is determined more by the intermediate k-space re-gridding step during reconstruction^{21,22}. Precise characterization of such effects on the resultant image quality is therefore non-trivial and their impact on the accuracy of the strain measurements is not fully known.

In addition, in previous studies, the SENC pulse sequence acquisition parameters were kept matched across the participating sites on a single vendor, but were not optimized in this study in a manner tailored to each site's specific systems hardware, and instead followed the parameters from a previous study². Further acquisition parameter optimization would likely lead to improved image quality. Another limitation of this study is that SENC-CMR was only compared against regional wall thickening measured from cine-CMR images and not against other techniques that quantify myocardial strain due to lack of availability of pulse sequences and image analysis tools. Along this line, we note that detailed assessments of global strain measure reproducibility has been reported elsewhere^{23,24}, and that inter- and intra-observer reproducibility of regional strain in this study degenerated to the RV-septal wall insertion point selection step by the operator. This observation has also been reported using a larger study cohort²⁵.

Finally, the specific scope of this multi-center study focused on the examination of the presence of regional wall motion under the coordinated intermediate dose stress protocol across three centers, and we acknowledge that a larger study population cohort will

strengthen our findings. However, we also acknowledge that such effort moving forward using the defined 3-center protocol will require each site to revert to the 2016–2017 study protocol that to our knowledge is retired at each site; the vendor MRI acquisition software at each participating site is at least one software release ahead at this time. While further investigations across technical advances in terms of both acquisition and software post-processing may potentially further increase the sensitivity of our hypothesized marker measurements, our findings nonetheless support the hypothesis regarding the assessment of regional LV strain per each AHA segment to better quantify cardiac function.

5. CONCLUSION

Real-time SENC has the potential to rapidly and reliably quantify regional myocardial strain. In this multi-center study, we found that, when measured using SENC, changes in circumferential and longitudinal strain during intermediate-dose dobutamine infusion can be unmasked prior to and in a manner more sensitive than the development of any quantifiable changes in wall thickening. These findings reinforce the validity of this technique in the clinical setting and further underscore the clinical importance of quantifying regional left ventricular function using strain analysis.

AUTHOR ACKNOWLEDGEMENTS

This study was funded by the following sources: Philips (KK, SK, ARP), Myocardial Solutions (KK, DD, SK, ARP), and an NIH Award (KK, NIH K25 HL141634).

References:

1. Hoit BD. Strain and strain rate echocardiography and coronary artery disease. *Circ Cardiovasc Imaging* 2011;4(2):179–190. [PubMed: 21406664]
2. Korosoglou G, Lossnitzer D, Schellberg D, et al. Strain-encoded cardiac MRI as an adjunct for dobutamine stress testing: incremental value to conventional wall motion analysis. *Circ Cardiovasc Imaging* 2009;2(2):132–140. [PubMed: 19808579]
3. Wayte SC, Redpath TW. Cine magnetic resonance imaging of pulsatile cerebrospinal fluid flow using CSPAMM. *Br J Radiol* 1994;67(803):1088–1095. [PubMed: 7820401]
4. Osman NF, Kerwin WS, McVeigh ER, Prince JL. Cardiac motion tracking using CINE harmonic phase (HARP) magnetic resonance imaging. *Magn Reson Med* 1999;42(6):1048–1060. [PubMed: 10571926]
5. Osman NF, McVeigh ER, Prince JL. Imaging heart motion using harmonic phase MRI. *IEEE Trans Med Imaging* 2000;19(3):186–202. [PubMed: 10875703]
6. Aletras AH, Ding S, Balaban RS, Wen H. DENSE: displacement encoding with stimulated echoes in cardiac functional MRI. *J Magn Reson* 1999;137(1):247–252. [PubMed: 10053155]
7. Osman NF. Detecting stiff masses using strain-encoded (SENC) imaging. *Magn Reson Med* 2003;49(3):605–608. [PubMed: 12594769]
8. Pan L, Stuber M, Kraitchman DL, Fritzges DL, Gilson WD, Osman NF. Real-time imaging of regional myocardial function using fast-SENC. *Magn Reson Med* 2006;55(2):386–395. [PubMed: 16402379]
9. Ibrahim e-S, Stuber M, Fahmy AS, et al. Real-time MR imaging of myocardial regional function using strain-encoding (SENC) with tissue through-plane motion tracking. *J Magn Reson Imaging* 2007;26(6):1461–1470. [PubMed: 17968902]
10. Schuster A, Kutty S, Padiyath A, et al. Cardiovascular magnetic resonance myocardial feature tracking detects quantitative wall motion during dobutamine stress. *Journal of Cardiovascular Magnetic Resonance* 2011;13(1):58. [PubMed: 21992220]

11. Moody WE, Taylor RJ, Edwards NC, et al. Comparison of magnetic resonance feature tracking for systolic and diastolic strain and strain rate calculation with spatial modulation of magnetization imaging analysis. *J Magn Reson Imaging* 2015;41(4):1000–1012. [PubMed: 24677420]
12. Korosoglou G, Lehrke S, Wochele A, et al. Strain-encoded CMR for the detection of inducible ischemia during intermediate stress. *JACC Cardiovasc Imaging* 2010;3(4):361–371. [PubMed: 20394897]
13. Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *J Am Soc Echocardiogr* 2015;28(1):1–39.e14. [PubMed: 25559473]
14. Pedrizzetti G, Claus P, Kilner PJ, Nagel E. Principles of cardiovascular magnetic resonance feature tracking and echocardiographic speckle tracking for informed clinical use. *J Cardiovasc Magn Reson* 2016;18(1):51. [PubMed: 27561421]
15. Hamdan A, Thouet T, Kelle S, et al. Strain-encoded MRI to evaluate normal left ventricular function and timing of contraction at 3.0 Tesla. *J Magn Reson Imaging* 2009;29(4):799–808. [PubMed: 19306402]
16. Korosoglou G, Youssef AA, Bilchick KC, et al. Real-time fast strain-encoded magnetic resonance imaging to evaluate regional myocardial function at 3.0 Tesla: comparison to conventional tagging. *J Magn Reson Imaging* 2008;27(5):1012–1018. [PubMed: 18407541]
17. Neizel M, Lossnitzer D, Korosoglou G, et al. Strain-encoded MRI for evaluation of left ventricular function and transmural in acute myocardial infarction. *Circ Cardiovasc Imaging* 2009;2(2):116–122. [PubMed: 19808577]
18. Korosoglou G, Futterer S, Humpert PM, et al. Strain-encoded cardiac MR during high-dose dobutamine stress testing: comparison to cine imaging and to myocardial tagging. *J Magn Reson Imaging* 2009;29(5):1053–1061. [PubMed: 19388131]
19. Korosoglou G, Gitsioudis G, Voss A, et al. Strain-encoded cardiac magnetic resonance during high-dose dobutamine stress testing for the estimation of cardiac outcomes: comparison to clinical parameters and conventional wall motion readings. *J Am Coll Cardiol* 2011;58(11):1140–1149. [PubMed: 21884952]
20. Tsai CM, Nishimura DG. Reduced aliasing artifacts using variable-density k-space sampling trajectories. *Magn Reson Med* 2000;43(3):452–458. [PubMed: 10725889]
21. Beatty PJ, Nishimura DG, Pauly JM. Rapid gridding reconstruction with a minimal oversampling ratio. *IEEE Trans Med Imaging* 2005;24(6):799–808. [PubMed: 15959939]
22. Fessler JA. On NUFFT-based gridding for non-Cartesian MRI. *J Magn Reson* 2007;188(2):191–195. [PubMed: 17689121]
23. Giusca S, Korosoglou G, Zieschang V, et al. Reproducibility study on myocardial strain assessment using fast-SENC cardiac magnetic resonance imaging. *Sci Rep* 2018;8(1):14100. [PubMed: 30237411]
24. Lapinskas T, Zieschang V, Erley J, et al. Strain-encoded cardiac magnetic resonance imaging: a new approach for fast estimation of left ventricular function. *BMC Cardiovasc Disord* 2019;19(1):52. [PubMed: 30836942]
25. Shuaibi A, Matsumoto K, Dabir D, et al. Inter-Observer Reproducibility of Regional Myocardial Strain using Strain-ENCode (SENC) Cardiac MRI – A Multicenter Validation Study. Paper presented at: Biomedical Engineering Society Annual Meeting; Oct 17–20, 2018; Atlanta, GA.

Figure 1:

Schematics of Strain Encoding (SENC) and quantitative Strain Maps. On the left, the quantitative measure of strain that is encoded via tagging pulses prescribed parallel to the imaging plane and across the slice thickness is shown. The color scheme corresponds to tension force in red, reduced strain in yellow, moderate strain in green, and normal strain in blue. On the right, end-systolic images of a short-axis cine-CMR with and without SENC-CMR derived quantitative strain measurements overlaid in the form of the strain color-map are shown.

Figure 2:

Dobutamine Stress Protocol (rest followed by intermediate-dose stress). Cine 2, 3, 4-chamber and SENC slices were matched. Three short-axis cine and SENC slices were also obtained at the basal, mid, and apical level of the LV.

Figure 3. Normal SENC Example.

An end-systolic frame from an SENC image obtained in the 4-chamber imaging plane is shown. The image on the left is acquired during resting conditions and the image on the right is acquired during stress conditions. Display is from commercial software Myostrain 4.1.

Figure 4. Abnormal SENC Example.

End-systolic Cine (top) and SENC (bottom) images acquired in an individual with a severe left anterior descending artery stenosis. Images are acquired during resting conditions are shown on the left and those acquired during stress conditions are shown on the right. Normal wall motion is noted on the cine-CMR images during rest and stress (orange arrows); however, abnormal strain is detected during stress but not rest on the SENC-CMR images (white arrows). SENC display is shown using at two of the four levels; at moderate (green) and normal (blue).

Table 1.

Clinical Characteristics and Imaging Data

Parameter	Overall (n=29)
CLINICAL	
Age (year)	63 ± 11
Male gender	59% (16)
Blood Pressure (BP)	
Systolic / Diastolic BP at rest (mmHg)	$126 \pm 19 / 71 \pm 14$
Systolic / Diastolic BP at stress (mmHg)	$146 \pm 22 / 72 \pm 15$
Heart Rate at rest (beats per minute)	71 ± 12
Heart Rate at stress (beats per minute)	90 ± 30
Risk Factors	
Hypertension	48% (14)
Hyperlipidemia/hypercholesterolemia	38% (11)
Diabetes mellitus	13% (4)
Tobacco use	24% (7)
Family history	17% (5)
History of coronary artery disease	38% (11)
History of prior revascularization	24% (7)
CARDIAC MR	
Ejection fraction (%)	64 ± 8
End-diastolic volume (ml)	144 ± 33
End-systolic volume (ml)	53 ± 20
LV Mass Index (g)	102 ± 26
CORONARY ANGIOGRAM	
Any Coronary Artery Stenosis 50%	45% (13)
1-vessel 50%	7% (2)
2-vessel 50%	7% (2)
3-vessel 50%	31% (9)

Table 2.

Relationship between Percent Wall Thickening and Coronary Stenosis Severity

Stenosis	0–50%	50–75%	>75%
Wall Thickening at Rest (%)	0.50 (0.39–0.58)	0.47 (0.34–0.56)	0.47 (0.39–0.58)
Wall Thickening at Stress (%)	0.51 (0.41–0.58)	0.53 (0.47–0.61)	0.48 (0.39–0.57)

Table 3.

Relationship between Regional Longitudinal and Circumferential Strain and Coronary Stenosis Severity

Stenosis	0–50%	50–75%	>75%
Longitudinal Strain			
at Rest (%)	–17.3 (–21.2 – –13.6)	–17.5 (–21.0 – –14.5)	–16.0 (–19.7 – –12.6)
at Stress (%)	–17.4 (–21.8 – –12.5)	–17.3 (–22.1 – –13.6) ^{*1}	–13.7 (–19.5 – –9.9) ^{*2}
Circumferential Strain			
at Rest (%)	–18.3 (–22.0 – –12.9)	–20.0 (–23.4 – –13.6)	–17.9 (–23.7 – –14.7) ^{\$1}
at Stress (%)	–18.8 (–22.6 – –13.9)	–18.0 (–22.3 – –12.2)	–16.7 (–20.8 – –12.7) ^{\$2}

*, \$ - Statistically significant differences were observed between ^{*1} and ^{*2} (p < 0.05); and ^{\$1} and ^{\$2} (p < 0.001)