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Evaluation of coronary artery disease using myocardial elastography with diverging wave imaging: validation against myocardial perfusion imaging and coronary angiography

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Abstract

Myocardial elastography (ME) is an ultrasound-based technique that can image 2-D myocardial strains. The objectives of this study were to show that 2-D myocardial strains can be imaged with diverging wave imaging and are different in average between normal and coronary artery disease (CAD) patients. In this study, 66 patients with symptoms of CAD were imaged with ME prior to a nuclear stress test or an invasive coronary angiography. Radial cumulative strains were estimated in all patients. The end-systolic radial strain in the total cross-section of the myocardium in normal subjects ($17.9 \pm 8.7\%$) was significantly higher than in patients with reversible perfusion defect ($6.2 \pm 9.3\%$, $p < 0.001$) and than in patients with significant ($-0.9 \pm 7.4\%$, $p < 0.001$) and non-significant ($3.7 \pm 5.7\%$, $p < 0.01$) lesions. End-systolic radial strain in the left anterior descending (LAD), the left circumflex (LCX) and the right coronary artery (RCA) territory was found to be significantly higher in normal subjects than in CAD patients. These preliminary findings indicate that end-systolic radial strain measured with ME is higher on average in healthy subjects compared to CAD patients and indicates that ME has the potential to be used for non-invasive, radiation free early detection of CAD.

Keywords

Cardiac strain imaging; Diverging wave imaging; Coronary artery disease; Myocardial perfusion imaging; Coronary angiography

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Conflict of interest

The authors declare no conflicts of interest.

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Introduction

Coronary artery disease (CAD) is characterized by an insufficient blood flow in the coronary arteries and can lead to heart attack and myocardial infarct. It is the leading cause of death worldwide with 8.1 million deaths in 2013 (Roth, et al. 2015) and accounted for approximately 1 of every 7 deaths in the US in 2011 (Mozaffarian, et al. 2015). Various methods are used to diagnose ischemia such as ECG stress testing, stress echocardiography and nuclear stress test or to assess coronary anatomy using coronary computed tomography angiography or magnetic resonance coronary angiography (Montalescot, et al. 2013). Stress echocardiography is an ultrasound technique and therefore has the advantages of being portable, low risk and of high temporal resolution. However, it requires the patient to be stressed either by exercising or pharmacologically and is mainly based on a visual assessment of wall motion abnormalities which is subjective. Studies have focused on left-ventricular systolic function as it has been reported to be a strong predictor of long-term survival in patients affected by various cardiac diseases (Svealu, et al. 2008, Vasan, et al. 1999).

Echocardiographic strain imaging has been developed as an ultrasound-based method to objectively and quantitatively assess myocardial deformation during stress or at rest (Gaibazzi, et al. 2014, Zuo, et al. 2015). Strain imaging offers the advantage of distinguishing tissue motion with deformation from tissue motion without significant deformation and several studies have shown that strain and strain rate imaging are sensitive to myocardial damage after myocardial ischemia or infarction (Edvardsen, et al. 2001, Voigt, et al. 2003, Weidemann, et al. 2007, Winter, et al. 2007). The two commercially available cardiac strain imaging techniques are tissue Doppler imaging (TDI) (Hoffmann, et al. 2010, Urheim, et al. 2000) and speckle tracking echocardiography (STE) (Biering-Sorensen, et al. 2014, Gaibazzi, et al. 2014). However, TDI is angle dependent and has low spatial resolution and STE is performed with B-mode images which are based on the envelope of the radiofrequency (RF) signals. Previous studies have shown that RF signals provide better performance than envelope signals for tissue deformation estimation (Alam and Ophir 1997, Ma and Varghese 2013). Myocardial Elastography (ME) is an angle-independent technique for 2-D myocardial strain imaging at high temporal resolution using RF signals (Zervantonakis, et al. 2007). This technique has been validated against tagged magnetic resonance imaging and was shown to be able to differentiate normal from reperfused myocardium (Lee, et al. 2008). A more recent study has shown that ME was capable of detecting, identifying and characterizing down to 40% blood flow reduction in the left anterior descending artery (LAD) of a canine model *in vivo* (Lee, et al. 2011). In these previous studies, high frame rates were achieved while keeping a high beam density by using ECG-gating to assemble small sectors of RF signals acquired at different heartbeats into a full echocardiographic view. This composite sector data acquisition can not only cause mismatches between sectors which can lead to motion artifacts but also require the patients to hold their breath during the 20 s duration of acquisition to minimize motion artifacts, which can be challenging for diseased patients.

In this study, the performance of ME by acquiring RF signals at high frame rates during a single heart cycle is investigated. In order to acquire the full echocardiographic view during

a single heart cycle at high frame rate, diverging wave imaging will be used. Previous studies have shown that diverging wave imaging can be used to image the heart with high contrast at high temporal resolution (Papadacci, et al. 2014) or follow the propagation of the electromechanical wave in the heart at high temporal resolution by estimating inter-frame strains (Provost, et al. 2013) and was validated against electrical mapping (Grondin, et al. 2016). Diverging wave imaging has also been used to image cardiac end-systolic cumulative axial strains in patients with an intracardiac transducer to differentiate healthy tissue from RF lesion (Grondin, et al. 2015). The feasibility and precision of estimating axial and lateral cardiac strain using diverging wave imaging has also been shown in healthy volunteers but without accumulating the strain over systole (Bunting, et al. 2014). However, the use of diverging wave imaging for investigating normal and CAD patients by comparing end-systolic accumulated cardiac strain has not been investigated yet.

The objectives of this study are to show that 2-D myocardial strains can be imaged in normal and CAD patients with diverging wave imaging and to investigate the difference in end-systolic radial strains measured between normal and CAD patients.

Methods

Study population

In this study, end-systolic radial strain estimated with ME was compared to two widely used techniques to diagnose CAD. Patients with symptoms of CAD and scheduled for a nuclear stress test or an invasive coronary angiography were screened. Patients with prior known myocardial infarct, stent, bypass surgery, heart transplants, severe aortic stenosis, hypertrophic heart, weight over 220 pounds or with a poor acoustic window were excluded from the study. All the patients who did not have those exclusion criteria and who gave their informed consent were recruited. Out of the 66 total number of patients recruited for this study, 17 were assessed by coronary angiography and 49 were assessed by nuclear perfusion imaging. The study protocol was approved by an Institutional Review Board of Columbia University and informed consent was obtained before the study.

Myocardial Elastography

The patients were scanned with ultrasound prior to and on the same day as their nuclear stress test or angiography. None of the patients had any sedation prior to the ultrasound scan. The heart was imaged in short-axis view at the basal, mid and apical level. A 2.5 MHz center frequency transducer (P4-2, ATL/Philips, Andover, MA) operated by a Verasonics system (V-1, Verasonics, Kirkland, WA) was used to scan the patients. The ECG signal was acquired synchronously with the ultrasound data using an ECG unit (77804A, HP, Palo Alto, CA) connected to a data acquisition system (NI USB-6210, National Instruments, Austin, TX) and triggered by the Verasonics. In order to obtain a large field of view at high frame rate (2000 Hz), diverging wave imaging was used by placing the focus 10 mm behind the surface of the transducer (Provost, et al. 2013, Provost, et al. 2011). Channel radiofrequency (RF) data were acquired at 2000 Hz on the 64 elements of the probe during 2 s and sampled at 10 MHz. A standard delay-and-sum method was used to reconstruct the entire image for each single diverging beam transmit (Grondin, et al. 2015). The image was reconstructed on

a polar grid of 256 lines, sampled axially at 20 MHz (i.e. 38.5 μm) with an imaging depth of 20 cm and a field of view of 90°. Conventional B-mode images were also acquired during 1.5 s. Motion estimation was performed at 500 Hz using normalized 1-D (axial) cross-correlation (Luo and Konofagou 2010) in a 2-D (axial and lateral) search (Konofagou and Ophir 1998) with a window length of 5.9 mm and 90% overlap. The lateral search range was 1 beam with a 10:1 linear interpolation factor. A 3x3 mm median filter was applied to the axial and lateral displacements in order to reduce outliers associated with peak-hopping artifacts. The axial and lateral displacements were accumulated during systole which is commonly defined using ECG landmarks such as the RT interval (Budoff and Shinbane 2010). However, as shown by Figure 1, the axial displacement M-mode exhibits some transient motion between the R peak and the onset of the inward motion, consistently observed in all patients. Since this transient motion can affect the displacement accumulation, systole was defined from the axial displacement M-mode during the inward motion. More specifically, the onset of systole was manually selected and defined as the beginning of the longest phase during which the anterior wall exhibited a downward motion (in blue) while the inferior wall concomitantly exhibited an upward motion (in red).

The myocardium was manually segmented and automatically tracked (Luo and Konofagou 2008) throughout the systolic phase. Axial and lateral Lagrangian strains were estimated from the axial and lateral displacements respectively using a least square estimator implemented with Savitzky-Golay filters (Luo, et al. 2004). Radial strains were derived from the axial and lateral strains with the origin of the polar coordinate system at the centroid of the segmented myocardium. Previous studies have found that end-systolic radial strain was able to differentiate a reperfused from a normal myocardium (Lee, et al. 2008) and to characterize early onset of ischemia (Lee, et al. 2011). In this study, for each patient, the end-systolic radial strain was averaged in the entire cross-section of the myocardium in the short-axis view. The reproducibility of this technique was investigated in a healthy subject and in a CAD patient from Group 1 and Group 2. The end-systolic radial strain was compared between two acquisitions from consecutive cardiac cycles or after removing and repositioning the probe. Radial strains were obtained from ultrasound acquisition in short-axis view which is more convenient for assessing the distribution of each main coronary artery.

Territory selection

The myocardium was divided into three major coronary vascular territories as defined by the general assumption about the most frequent vascular distribution pattern as illustrated in (Lauerma, et al. 1997). Each of the three regions of interest (ROIs) was manually selected from the B-mode image. The LAD perfuses the antero-septal region, the left circumflex artery (LCX) perfuses the lateral region and the right coronary artery (RCA) perfuses the inferior region. The end-systolic radial strain was averaged in each of the three territories.

Myocardial perfusion imaging

At rest, the patient was injected with Tc99m Sestamibi and rest Gated perfusion images of the heart were obtained using a dual head Philips Precedence SPECT/CT camera (Philips Healthcare, Amsterdam, Netherlands) equipped with low-energy, high-resolution collimators.

Each patient was stressed via Bruce treadmill exercise protocol if capable of ambulating or via a pharmacologic vasodilator agent (regadenoson or adenosine, depending on physician preference). At peak stress, patients were injected with Tc99m Sestamibi and again imaged on specT/CT camera. The tomographic slices were reconstructed in 3 orthogonal planes (short axis, horizontal long axis and vertical long axis). The reconstructed images were analyzed using both visual and quantitative analysis. All images were assessed by a nuclear cardiology board certified physician.

Coronary angiography

The patients were brought to the procedure room and placed on the table. Left and right coronary angiography was performed by advancing a catheter to the aorta and positioning it in the ostium of the left main and the right coronary, respectively. Angiography was performed in multiple projections. Omnipaque (GE Healthcare, Chicago, IL) was used as a contrast agent. All images were assessed by a cardiology board certified physician. Patients with >50% obstruction in a coronary vessel on the angiogram were considered to have significant CAD whereas patients with $\leq$ 50% obstruction were considered to have non-significant CAD.

Statistical analysis

All statistical analyses were performed using Matlab (Mathworks, Natick, MA). A chi-square test was used to investigate if the distribution of categorical variables in Table 1 were different. The mean and standard deviation of end-systolic mean radial strain across patients were computed for the normal subjects, the patients with reversible myocardial perfusion defect (Group 1), the patients with non-significant CAD and the patients with significant CAD (Group 2) for the total cross-section of the myocardium as well as for each ROI. A Lilliefors test was used to determine if the end-systolic mean radial strain for every group of patients in each territory and in the total cross-section followed a normal distribution. The end-systolic mean radial strains in the normal group and in Group 1 were normally distributed in each territory and in the total cross-section and a two-sample t-test was used to compare each quantity. A one-way analysis of variance (ANOVA) test for normally distributed quantities and a Kruskal-Wallis test for non-normally distributed quantities were performed to compare the end-systolic mean radial strain between the normal, the non-significant and the significant CAD patients. For the normal subjects, the end-systolic mean radial strain was computed at the mid-level short axis view whereas for the CAD patients it was computed at the level (apical, middle or basal) with abnormal perfusion. If several levels had abnormal perfusion for a given CAD patient, the mid-level was used due to higher strain estimation quality at this level.

Results

Among all the recruited patients, 36 were normal (34 patients with normal myocardial perfusion assessed by nuclear stress test and 2 patients with normal coronary arteries determined by angiography), 15 had myocardial ischemia detected by nuclear perfusion (Group 1) and 15 had coronary stenosis determined by angiography (Group 2). The patient population is described in Table 1. For the patients who had coronary angiography, six were

found to have non-significant CAD whereas nine patients were found to have significant CAD. Six patients were found to have single vessel CAD, two patients were found to have double vessel CAD and seven patients were found to have triple vessel CAD (significant and/or non-significant). The number of patients with significant or non-significant CAD for each coronary artery is detailed in Table 1.

Strain imaging

All healthy subjects and CAD patients were in sinus rhythm during ultrasound data acquisition. The reproducibility of ME with diverging wave imaging was investigated in a normal subject, a CAD patient from Group 1 and a CAD patient from Group 2. Left-ventricular, end-systolic radial strains in the total cross-section were found to be $26.1 \pm 31.5\%$ vs. $25.1 \pm 38.3\%$ for two consecutive cardiac cycles in a normal subject (Figure 2); $6.1 \pm 15.9\%$ vs. $10.8 \pm 17.7\%$ after removing and repositioning the probe in a patient with a reversible perfusion defect in the inferior wall (Figure 3.A and 3.B); $0.6 \pm 11.8\%$ vs. $0.1 \pm 7.0\%$ for two consecutive cardiac cycles in a patient with 50% occlusion in the ostium of the 1st diagonal of the LAD (Figure 3.C and 3.D). Similar patterns were obtained for both acquisitions for the normal and the CAD patients. Left-ventricular, end-systolic radial strain in a normal subject is shown in Figure 2. Positive radial strains in red show radial thickening of the myocardium. Myocardial Elastography was also performed in CAD patients. Left-ventricular, end-systolic radial strain is shown in a patient with a reversible perfusion defect in the inferior wall (Figure 3.A and 3.B). Radial thickening (in red) was measured in the anterior and septal regions whereas radial thinning (in blue) was measured in the inferior and lateral regions. Left-ventricular, end-systolic radial strain is shown in a patient with 50% occlusion in the ostium of the 1st diagonal of the LAD (Figure 3.C and 3.D). Radial thickening was measured in the anterior, lateral and inferior regions whereas radial thinning was measured in the septal region.

Statistical analysis

The myocardium was divided into three territories, each of which was perfused by a coronary artery (Lauerma, et al. 1997). The mean and standard deviation of end-systolic radial strain was computed in the total cross-section of the myocardium as well as in each territory for the normal subjects and compared to those obtained in Group 1 of the CAD patients detected by nuclear perfusion imaging (Figure 4) and to the Group 2 of CAD patients detected by coronary angiography (Figure 5). The end-systolic radial strain in the total cross-section of the myocardium in healthy subjects ($17.9 \pm 8.7\%$) was significantly higher than in Group 1 of CAD patients ($6.2 \pm 9.3\%$, $p < 0.001$). End-systolic radial strain in the LAD territory was found to be significantly higher in healthy subjects ($18.0 \pm 10.4\%$) than in patients with perfusion defect in regions perfused by the LAD ($3.2 \pm 5.2\%$, $p < 0.01$). End-systolic radial strain in the LCX territory was found to be significantly higher in healthy subjects ($17.7 \pm 12.6\%$) than in patients with perfusion defect in regions perfused by the LCX ($1.0 \pm 10.6\%$, $p < 0.01$). End-systolic radial strain in the RCA territory was found to be significantly higher in healthy subjects ($16.8 \pm 13.2\%$) than in patients with perfusion defect in regions perfused by the RCA ($1.2 \pm 5.5\%$, $p < 0.01$).

The end-systolic radial strain in the total cross-section of the myocardium in healthy subjects ($17.9 \pm 8.7\%$) was significantly higher than in significant CAD patients ($-0.9 \pm 7.4\%$, $p < 0.001$) and in non-significant CAD patients ($3.7 \pm 5.7\%$, $p < 0.01$). End-systolic radial strain in the LAD territory was found to be significantly higher in healthy subjects ($18.0 \pm 10.4\%$) than in patients with obstructed LAD ($2.3 \pm 7.0\%$, $p < 0.01$) and patients with non-significant LAD ($1.7 \pm 10.3\%$, $p < 0.001$). End-systolic radial strain in the LCX territory was found to be significantly higher in healthy subjects ($17.7 \pm 12.6\%$) than in patients with obstructed LCX ($2.4 \pm 6.6\%$, $p < 0.05$) and patients with non-significant LCX ($6.6 \pm 13.5\%$, $p < 0.05$). The end-systolic radial strain in the RCA territory was found to be significantly higher in healthy subjects ($16.8 \pm 13.2\%$) than in patients with obstructed RCA ($-2.9 \pm 11.8\%$, $p < 0.05$) and patients with non-significant RCA ($-1.8 \pm 15.4\%$, $p < 0.001$). No significant difference was also found between non-significant and significant CAD patients in the total cross-section of the myocardium or in any territory.

Discussion

Non-invasive and radiation-free detection and characterization of coronary artery disease (CAD) can avoid unnecessary procedures and radiation exposure such as coronary angiography or nuclear stress-test. It has been reported that only 35–40% of patients referred for a nuclear stress test have at least one reversible defect (Hoiland-Carlsen, et al. 2006, Papadacci, et al. 2014), indicative of ischemia and 53–62% of patients referred for a coronary angiography turn out to have normal or non-significant CAD (Hoiland-Carlsen, et al. 2006, Patel, et al. 2010). Myocardial Elastography (ME) is an ultrasound technique that can image myocardial strains at high frame rate using the radiofrequency (RF) signals. High frame rate imaging can be achieved using sector scan acquisition of focused beams and ECG gating. This technique requires long breath-holding times to reduce motion artifacts and uses acquisition from multiple cardiac cycles. ME has been shown capable of differentiating a normal heart from a reperfused heart or a heart with reduced blood flow in the left anterior descending (LAD) artery using ECG-gated acquisitions. Our objectives were to show that 2-D myocardial strain can be imaged in normal and CAD patients during a single heart cycle at high temporal resolution and to investigate the difference in end-systolic radial strain between normal and CAD patients.

The reproducibility of our technique was investigated for normal and CAD patients. Left-ventricular, end-systolic radial strains were obtained for each patient during two consecutive cardiac cycles or after removing and repositioning the probe. Similar radial strains were obtained for both acquisitions for the normal and CAD patients, with better reproducibility of ME with diverging waves for consecutive cardiac cycles than after removing and repositioning the probe. Figure 2 shows the left-ventricular, end-systolic radial strains in a normal subject. Radial thickening of the myocardium is observed in the entire cross-section. This indicates that ME with diverging wave imaging can be used to image 2-D myocardial strains transthoracically during a single heart cycle.

Left-ventricular, end-systolic radial strains were also imaged for CAD patients. Figure 3.A and 3.B show radial strain for a patient with a reversible perfusion defect in the inferior wall, indicative of ischemia. The anterior and septal regions indicate radial thickening whereas the

inferior and lateral regions show thinning. This region of opposite strain can be due to passive tethering caused by the ischemia. This effect has been reported in previous studies (Holmes, et al. 2005), predicted by theoretical models (Lee, et al. 2007) and imaged by ME and tagged-MRI (Lee, et al. 2008). Figure 3.C and 3.D show radial strain for a patient with 50% occlusion in the ostium of the 1st diagonal of the LAD. The anterior, lateral and inferior region indicates radial thickening whereas thinning is observed in the septal wall, which is perfused by the LAD.

Figure 4 compares the left-ventricular, end-systolic radial strain in normal and ischemic patients across the entire cross-section of the myocardium as well as in the LAD, LCX and RCA territories. Ischemic patients were found to have significantly lower radial strains than normals across the total cross-section of the myocardium as well as in the LAX, LCX and RCA territories. This suggests that ME can discriminate normal from CAD patients. Figure 5 compares the left-ventricular, end-systolic radial strain in normal subjects, non-significant and significant CAD patients across the entire cross-section of the myocardium as well as in the LAD, LCX and RCA territories. Patients with non-significant and significant CAD were found to have significantly lower radial strains than normal subjects across the total cross-section of the myocardium as well as in the LAD, LCX and RCA territories. Previous studies reported that non-significant lesions can cause ischemia (Curzen, et al. 2014, Park, et al. 2015, Schuijf, et al. 2006). However, in this study, no significant difference in radial strain was found between patients with non-significant CAD and patients with at least one obstructed coronary in the total cross-section or in any territory. The significant difference between normal and ischemic patients or patients with non-significant CAD indicates that ME could be used for early detection of CAD. However, the level of stenosis was visually assessed. Therefore the classification between significant and non-significant coronary stenosis can be impacted by the subjectivity of the operator. In addition, among the 15 patients found with stenosis, 12 were reported to have had a clinical echocardiogram independently of this study and only five patients were found to have wall motion abnormality. Among the 7 patients reported with normal wall motion, 4 had non-significant occlusions and 3 had significant occlusions. This indicates that the ultrasound technique presented in this study can measure lower strain in patients with coronary stenosis compared to healthy subjects whereas wall motion scoring assessed by clinical echocardiography was not sensitive enough to coronary stenosis in most of the patients. In this study, 36 patients were normal, 15 had reversible perfusion defect and 15 had significant or non-significant stenosis. A larger scale study should be carried out to determine if these preliminary findings are confirmed in the total cross-section of the myocardium as well as in the LAD, LCX and RCA territories. A higher number of patients would also be required to investigate the effect of the severity of the stenosis on the strain measurements.

This study has several limitations. The groups of CAD patients and normal subjects had a few clinical characteristics differences that could have an effect on heart function. The proportion of males and of smokers was significantly higher among the CAD patients of Group 2 than among the normal subjects. On the other hand, there was proportion of patient with diabetes was significantly higher in the normal group than in both groups of CAD patients.

As mentioned previously, diverging wave imaging was used in this study to image the heart during a single heartbeat and at a relatively high frame rate to minimize decorrelation of RF signals. Therefore, the transmit waves were not focused and produced a lower lateral resolution compared to focused waves which can impair the lateral motion estimation. Lateral and radial strain estimation can thus be affected. However, our preliminary results suggest that the left-ventricular end-systolic radial strains are significantly different between normal and CAD patients. Since the acquisition and motion estimation frame rate were 2000 Hz and 500 Hz respectively, coherent compounding of diverging waves can be used to increase the lateral resolution while keeping a relatively high frame rate and still imaging within a single heart cycle. This technique is currently under investigation to be used with ME.

The division of the entire cross-section of the myocardium into the LAD, the LCX and the RCA territory, although based on anatomic landmarks was performed manually. This can affect the strain values attributed to each territory. An automated method would remove the subjectivity in the territory division. However, anatomic landmarks on B-mode images would require a better B-mode quality and, although a fair indicator, are not enough to determine with certainty the exact territory perfused by a coronary due to interindividual variability of coronary anatomy (Cerqueira, et al. 2002).

Left-ventricular, end-systolic radial strain is a characterization of the systolic function of the heart. However, the level of occlusion determined by invasive coronary angiography is an anatomical characterization of the severity of the stenosis. Although, in animal studies it has been shown that coronary flow rate begin to fall from 50% of diameter narrowing (Gould, et al. 1974), human studies has shown poor correlation between functional aspects such as coronary flow rate or myocardial perfusion and percent of stenosis determined by coronary angiography (Gaemperli, et al. 2008, Meijboom, et al. 2008, Tonino, et al. 2010, White, et al. 1984), which is an anatomical measurement. Therefore, a stenosis superior to 50% will not always cause strain reduction. This could partially explain why radial strains were not significantly different between the non-significant and significant CAD patients. This indicates that the relationship between the severity of coronary stenosis determined by coronary angiography and the left-ventricular, end-systolic strain is complex. The geometrical characteristics and composition of the plaque are additional factors the severity of the stenosis to predict ischemia (Gaur, et al. 2016). However, this study shows results consistent with other studies, which reported that CAD patients have lower radial (Xie, et al. 2016) and longitudinal (Biering-Sorensen, et al. 2014, Gaibazzi, et al. 2014) strain than healthy subjects.

Conclusions

In conclusion, 2-D myocardial strain can be imaged with diverging wave imaging during a single heart cycle. Left-ventricular, end-systolic radial strains measured with Myocardial Elastography were found to be higher in average in normal compared to CAD patients. These results, if confirmed by a larger scale study, could have a deep impact on CAD diagnosis as Myocardial Elastography offers promise as a screening tool for non-invasive, radiation free and early detection of CAD.

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Figure 1. Axial displacement M-mode (A) and corresponding ECG (B). Negative displacements in blue indicate downward motion and positive displacements in red indicates upward motion.

Figure 2.

Left-ventricular (LV), end-systolic radial strain for two consecutive cardiac cycles (A and B) in a normal patient. A similar pattern is obtained for both acquisitions which indicates good reproducibility of the technique. RV indicates right ventricle.

Figure 3.

Left-ventricular (LV), end-systolic radial strains at in a patient with a reversible perfusion defect in the inferior wall for two acquisitions after repositioning the probe (A and B) and in a patient with 50% occlusion in the ostium of the 1st diagonal of the LAD for two consecutive cardiac cycles (C and D).

Figure 4.

Left-ventricular, end-systolic mean radial strain ($\bar{\epsilon}$) in normal and ischemic (Group 1) patients in the total cross-section of the myocardium, the LAD, the LCX and the RCA territory. Error bars indicate standard deviation across the patients. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

Figure 5.

Left-ventricular, end-systolic mean radial strain ($\bar{\epsilon}$) in normal, non-significant and significant CAD patients (Group 2) in the total cross-section of the myocardium, the LAD, the LCX and the RCA territory. Error bars indicate standard deviation across the patients. *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

Table 1

Clinical characteristics of the 66 patients. Group 1 and group 2 are CAD patients detected by nuclear stress test and coronary angiography respectively.

	Normals (n = 36, 54.6%)	CAD Group 1 (n = 15, 22.7%)	CAD Group 2 (n = 15, 22.7%)	p-value Normals vs. CAD Group 1	p-value Normals vs. CAD Group 2
Age (years)	61.2 ± 11.2	68.0 ± 9.7	59.3 ± 12.9	0.064	0.510
Males, n (%)	15 (41.7%)	10 (66.7%)	11 (73.3%)	0.104	0.039
Hypertension, n (%)	20 (55.6%)	10 (66.7%)	11 (73.3%)	0.463	0.236
Diabetes, n (%)	13 (36.1%)	0 (0%)	1 (6.7%)	0.007	0.032
Smoker, n (%)	11 (30.1%)	4 (26.7%)	9 (60.0%)	0.781	0.050
Chronic kidney disease, n (%)	4 (11.1%)	2 (13.3%)	0 (0%)	0.822	0.179
Pulmonary disease, n (%)	0 (0%)	1 (6.7%)	1 (6.7%)	0.118	0.118
Coronary disease, n					
LAD	0	4	>50% 7 50% 8		
LCX	0	8	5 10		
RCA	0	9	5 10		

LAD: Left anterior descending artery, LCX: Left circumflex artery, RCA: Right coronary artery