Published in final edited form as:

Echocardiography. 2015 August ; 32(8): 1233–1240. doi:10.1111/echo.12832.

Quality Control and Reproducibility in M-mode, Two-dimensional, and Speckle Tracking Echocardiography Acquisition and Analysis: The CARDIA Study, Year-25 Examination Experience

Anderson C. Armstrong, MD, MSc, PhD^{1,2}, Erin P. Ricketts, MSPH¹, Christopher Cox, PhD¹, Paul Adler, RDCS, FASE¹, Alexander Arynchyn, PhD³, Kiang Liu, PhD⁴, Ellen Stengel¹, RDCS, Stephen Sidney, PhD⁵, Cora E. Lewis, MD, MSPH³, Pamela J. Schreiner, PhD⁶, James M. Shikany, PhD³, Kimberly Keck, RDCS¹, Jamie Merlo, RDCS¹, Samuel S. Gidding, MD⁷, and João A. C. Lima, MD¹

¹Johns Hopkins University, Baltimore, MD

²Universidade Federal do Vale do São Francisco, Petrolina, Brazil

³University of Alabama at Birmingham, Birmingham, AL

⁴Northwestern University, Chicago, IL

⁵Kaiser Permanente Division of Research, Oakland, CA

⁶University of Minnesota, Minneapolis, MN

⁷Nemours Cardiac Center, Wilmington, DE

Abstract

Introduction—Few large studies describe quality control procedures and reproducibility findings in cardiovascular ultra-sound, particularly in novel techniques such as Speckle Tracking (STE). We evaluate the echocardiography assessment performance in the CARDIA study Y25 examination (2010-2011) and report findings from a quality control and reproducibility program conducted to assess Field Center image acquisition and Reading Center (RC) accuracy.

Methods—The CARDIA Y25 examination had 3,475 echocardiograms performed in 4 US Field Centers and analyzed in a Reading Center, assessing standard echocardiography (LA dimension, aortic root, LV mass, LV end-diastolic volume [LVEDV], ejection fraction [LVEF]), and STE (2- and 4-chamber longitudinal, circumferential, and radial strains). Reproducibility was assessed using intra-class correlation coefficients (ICC), coefficients of variation (CV), and Bland-Altman plots.

Address for correspondence and reprint request: Anderson C. Armstrong or João A. C. Lima, Johns Hopkins University, Department of Cardiology/Cardiovascular Imaging, 600 N. Wolfe Street / Blalock 524, Baltimore, MD, USA, 21287-0409, Phone. 1-410-614-1284 / FAX. 1-410-614-8222, jlima@jhmi.edu, aarmst10@jhmi.edu.

There is no relevant conflict of interest regarding this manuscript.

Disclosures: The authors have no competing interests in this study.

Results—For standard echocardiography reproducibility, LV mass and LVEDV consistently had CV above 10% and aortic root below 6%. Intra-sonographer aortic root and LV mass had the most robust values of ICC in standard echocardiography. For STE, the number of properly tracking segments was above 80% in short-axis and 4-chamber and 58% in 2-chamber. Longitudinal strain parameters were the most robust and radial strain showed the highest variation. Comparing Field Centers with Echo RC STE readings, mean differences ranged from 0.4% to 4.1% and ICC from 0.37 to 0.66, with robust results for longitudinal strains.

Conclusion—Echocardiography image acquisition and reading processes in the CARDIA study were highly reproducible, including robust results for STE analysis. Consistent quality control may increase the reliability of echocardiography measurements in large cohort studies.

Keywords

Echocardiography; reproducibility; speckle tracking echocardiography; quality control

Introduction

Observational cohort studies are often used to estimate the effects of long-term risk exposures on cardiac and organ injury in large populations. Cohort studies should measure random variation from many sources, including biological variation and variation from the acquisition and measurement of study variables. Reproducibility, or precision, assesses this random variation and is a major indicator of quality in observational studies and clinical-based imaging laboratories.[1-3] High standards of quality in large observational studies are critical to validity of interpretation but achieving these high standards is challenging. [4, 5]

Standardization of image acquisition and reading procedures may reduce measurement error. [6] The Coronary Artery Risk Development in Young Adults (CARDIA) study prospectively investigates risk factor development during young adulthood and includes echocardiography assessment in its protocol.[7] Between 2010 and 2011, for the CARDIA study examination Year-25 (Y25), a significant effort was exerted to develop a reproducible echocardiography protocol that included 2-dimensional (2D), M-mode, and speckle tracking echocardiography (STE) images. These standardization efforts were implemented by Field Center sonographers and analysts at the Echocardiography Reading Center (Echo RC).

For this study, a standardized protocol for image acquisition at Field Centers was developed and then taught to both in-field sonographers and readers at the Reading Center. We implemented a sophisticated quality control process to determine the intra-sonographer, inter-sonographer, intra-reader, and inter-reader variation in the interpretation of both standard echocardiographic measurements and speckle tracking echocardiography measurements. We report below the results of this quality control activity.

Methods

Study design and sample

The CARDIA study has been previously described.[7] Briefly, 5,116 African-American and White participants aged from 18 to 30 years were recruited from community-based target

populations in 4 Field Centers (Birmingham, AL; Oakland, CA; Chicago, IL; and Minneapolis, MN) between 1985 and 1986. The contacts were stratified to achieve similar proportions according to race, age (< 25 and ≥ 25 years), gender, and education (with high school education or less than high school education).[7, 8] During the CARDIA Y25 exam (2010-2011), echocardiograms were performed at the 4 Field Centers and interpreted at the Echo RC (Johns Hopkins University, Baltimore, MD). A total of 3,499 participants attended the CARDIA Y25 examination between June 2010 and August 2011. From these, 3,475 (99.3%) underwent echocardiography exams; one participant withdrew his consent afterwards. Informed consent was obtained in all sites and the institutions committee on human research approved the study. The mean age was 50 ± 4 years, 43% were males, and 47% were African-American (participant clinical characteristics are shown in Supplement Table S2).

Echocardiography Scanning at Field Centers

The CARDIA Y25 echocardiography exam used the Artida™ cardiac ultrasound machine (Toshiba Medical Systems; Otawara, Japan) with a sector 30 BT transducer (fundamental frequency 2 - 5 MHz) to acquire and store in digital files M-mode, 2D, and STE images, among others. The full scanning protocol, developed by the Echo RC cardiologists and technologists, as well as members of the CARDIA Echo Committee, can be seen online at the CARDIA study website (<http://cardia2.dopm.uab.edu/>). The scanning protocol was designed to acquire the same echocardiographic views used in the Y5 CARDIA exam [9] and follow the most recent recommendations from the ASE.⁶[9] STE was acquired from 4-chamber and 2-chamber apical views and also from a short axis view at the level of the papillary muscles. As in previous studies using longitudinal strain, only as a matter of a time saving measure, the 3-chamber view was deferred. The STE initial pre-set included: frame rate = 46 fps (ensured > 40 fps); depth = 15cm; and scan range = 83%. For each view, three consecutive cardiac cycles were recorded during quiet respiration. For intra- and inter-sonographer reproducibility and to assess biological variation, 46 participants from the 4 sites were re-scanned by the same sonographer and another 42 participants were re-scanned by a second sonographer.

Echo RC personnel and an equipment application specialist performed initial training for Field Center sonographers, consisting of a 2-day workshop at the Echo RC and 2 additional days at each Field Center. The Field Center sonographers underwent continued monitoring during the entire period of participant examinations, including regular electronic communication and monthly conference calls, relating to image quality and protocol adherence. A pre-planned conference call held on December 14th, 2010 specifically addressed re-training procedures for STE readings during the image acquisitions by the sonographers at the Field Centers.

Echocardiography Reading Center Interpretation Process

Images were electronically transferred from the Field Centers to the Echo RC immediately after acquisition and then randomly distributed to one of 4 experienced analysts. The reading protocol was designed by the analysts and experienced cardiologists. Image quality was scored as poor, fair, good, or excellent, according to a standard protocol (Supplement Table

S1). Measurements for M-mode and 2D images were performed using Digiview™ (Digisonics Systems; Houston, Texas) and followed the ASE recommendations.[10, 11] Using a validated software, Advanced Cardiology Package Wall Motion 2D Tracking™ (Toshiba Medical Systems; Otawara, Japan), a semi-automatic assessment was performed by manual definition of endocardial border and wall thickness, followed by automatic border contours and myocardial tracking.

STE images were analyzed in a 16-segment basis for endocardial, mid-wall, and epicardial contours, using 4-chamber, 2-chamber, and short-axis views. Longitudinal strain and strain rate curves were assessed from 4- and 2-chamber views. Circumferential and radial strain and strain rates were assessed from the short-axis view.

The initial requirement for excluding STE segments was based on analysis of the strain curves. If a segment did not follow the general time to peak curve with the remaining segments, an extra step was taken to observe the moving image with the STE analysis overlay. Three scenarios resulted: (1) If the segment truly was not tracking due to reader error (endocardial points were not placed correctly and included too much trabeculation and not true cardiac tissue), then the study was re-analyzed/re-traced. Segments with inadequate myocardial tracking by visual evaluation were excluded if manual correction was unsuccessful; (2) If the segment wasn't tracking due to lung interference, poor image quality, etc., then that segment was excluded; and (3) If the segment wasn't tracking due to actual cardiac deformation, then the poor-tracking segment was kept in the analysis.

For each view, the STE image set (4-chamber, 2-chamber, or short-axis) was considered adequate for analysis if at least 3 segments were properly tracked. Rating one view as inadequate did not exclude all the participant image sets automatically, as each view was analyzed independently. In image sets adequate for STE analysis, peak strain values were calculated using the average of segmental peaks for all properly tracked segments during LV systole.

Using randomly selected exams, group critiquing and peer review were performed in weekly meetings with cardiologists and analysts. The same group also performed adjudication procedures for abnormal measurements and outliers, identified in periodic assessments.

Quality Control Assessment

The CARDIA Study has two primary focuses for quality control: (1) to assess errors and document the level of quality; and (2) to maintain and improve the quality of a subsequent collection of data.[7] A quarterly quality control assessment by the CARDIA Quality Control Committee evaluated the consistency of image acquisition and reading analysis.

To assess standard echocardiography reproducibility (inter-participant, intra-participant, inter-reader, and intra-reader), periodically, two 2D 4-chamber parameters (LV end-diastolic volume and ejection fraction) and three M-mode parameters (aorta root dimension, left atrial dimension, and LV mass) were evaluated. Additional intra- and inter-reader reproducibility was assessed for four left ventricular STE deformation parameters, averaging all adequately tracked segments in each view: (1) 4-chamber global peak longitudinal strain; (2) 2-chamber

global peak longitudinal strain; (3) global peak circumferential strain; and (4) total peak radial strain.

The Echo RC reader reproducibility was assessed for all four analysts. A subsample of images acquired in proportional numbers from each Field Center was randomly selected and blindly distributed to the analysts during regular readings. To assess inter-reader reproducibility in 2D and M-mode images, all 4 analysts read the same set of 200 images (total of 800 readings). The intra-reader reproducibility for 2D and M-mode images was assessed for all analysts by independently re-reading a set of 40 images (total of 160 readings). For intra-sonographer reproducibility, both sets of images from re-scanned participants were analyzed by the same reader at the Echo RC.

For STE analysis, values of strain parameters were compared according to the number of non-properly tracking segments. For the reproducibility evaluation in STE, a subset of 40 images was read by all 4 analysts for inter-reader reproducibility and independently re-analyzed by the same reader for intra-reader assessment. Additionally, we assessed the consistency of in-site STE measurement by Field Center sonographers. Just after acquisition, images were analyzed by Field Center sonographers with low experience in STE readings for peak longitudinal strain (total of 2832 participants; 1786 before sonographer re-training on STE) and peak circumferential strain (total of 2821 participants; 1788 before sonographer re-training on STE) immediately after image acquisition and compared to analysis at the Echo RC by experienced analysts.

Statistical Analysis

Continuous variables were described in mean values $\pm$ standard deviation (SD) and categorical variables in proportions. The distribution of the echocardiographic parameters was shown according to image quality. An additional analysis was performed if the variability in values was considered clinically meaningful. In this case, linear regression models were performed having the echocardiographic parameter as the dependent variable and image quality categories as the independent variable; adjusting for age, ethnicity, sex, body-mass index (BMI), and height as covariates.

Reproducibility was assessed computing intra-class correlation coefficient (ICC) and residual coefficient of variation (technical error) based on a linear mixed model. Bland-Altman plots and ICC compared STE measurements at the Field Center and at the Echo RC. The statistical analysis was performed using SAS 9.0 and STATA 11.0.

Results

Standard echocardiography

Of those that underwent echocardiography assessment in CARDIA Y25, the feasibility of standard measurements ranged from 90% for LV mass to 98% for aortic root, respectively. The majority of parameters had at least fair image quality. In comparison to LVEDV, LVEF, LA diameter, and aortic root measurements, LV mass had a mean value for poor quality images 31g (18%) above the overall value (Table 1). Adjusting for age, ethnicity, sex, BMI,

and height, participants with fair and good quality images had statistically lower LV mass compared to those with poor quality (Supplement Table S3).

Table 2 shows the reproducibility assessment of re-scanned participants in the Field Centers (total of 88 subjects: 23 from Chicago; 25 from Birmingham; 25 from Oakland; and 15 from Minneapolis). For inter-sonographer reproducibility, the coefficient of variation ranged from 6% to 12% for LVEF and LV mass, respectively. The coefficient of variation for intra-sonographer reproducibility was from 5% for LVEF to 11% for LVEDV. The overall ICC ranged from 0.6 for 2D LV ejection fraction to 0.9 for M-mode LV mass.

Inter- and intra-reader reproducibility regarding standard 2D and M-mode echocardiography parameters were assessed for Echo RC analysts. For the inter-reader reproducibility, the coefficient of variation ranged from 5.6% for the M-mode assessment of the aortic root diameter to 11.3% for the M-mode LV mass. However, LV mass and end-diastolic volumes had the highest ICC values (both = 0.87) in inter-reader assessment. The intra-reader reproducibility analyses found coefficient of variation ranging from 4.1% for aortic root diameter to 11.5% for LV mass, with the highest ICC (0.86) for M-mode aortic root dimension (Table 3).

Speckle tracking echocardiography

STE tracings were attempted in all 3,474 echocardiography exams, but were not technically feasible in 106 participants (3%). From the remaining 3,368 interpretable cases, 724 participants (22%) had all 16 segments interpretable. From the participants with interpretable STE images, the average of 5.1 segments per participant (85%) were considered properly tracking in the short-axis view; followed by 5.0 (83%) in the 4-chamber view and 3.5 (58%) for the 2-chamber view. The most frequent LV non-tracking segment in the short-axis view was the mid-anterior segment; apical-lateral in the 4-chamber view; and apical-anterior in the 2-chamber view (Figure 1). STE parameter standard deviation and coefficient of variation tended to increase as the number of excluded segments increased (Table 4).

Table 5 shows the reproducibility results for STE parameters. For inter-reader reproducibility, the coefficient of variation ranged from 10% for 4-chamber peak longitudinal strain to 15% for peak radial strain; while the ICC ranged from 0.6 for 4-chamber longitudinal strain to 0.8 for radial strain. In the intra-reader reproducibility assessment, the coefficient of variation ranged from 6% to 12% for 2-chamber longitudinal strain and radial strain, respectively. The intra-reader ICC ranged from 0.8 to 0.9 for 4-chamber longitudinal strain and radial strain, respectively.

When STE reading by sonographers at the Field Centers with limited experience in STE were compared to experienced readers' analysis at the Echo RC, peak longitudinal strain before re-training showed a mean difference of -0.35%, with 95% limits of agreement between -5.11% and 4.42%; and ICC = 0.60. After re-training, the mean difference was 0.08% (95% limits of agreement = -4.23, 4.38) and ICC was 0.66. For peak circumferential strain, the mean difference before re-training was -4.08% (95% limits of agreement =

-12.53, 4.37) and ICC was 0.23; after re-training the mean difference was -2.58% (95% limits of agreement = -9.53, 4.38) and ICC was 0.37.

Discussion

This study describes quality control procedures and reproducibility findings for a large cohort of bi-racial adults undergoing a protocol of echocardiography that includes 2D, M-mode, and STE techniques. We report the quality control measures used in the echocardiography assessment and analysis in the CARDIA Y25 examination. A robust profile of echocardiography reproducibility was found for 2D, M-mode, and STE techniques. The consistently low technical error of about 11% or less and the high values of ICC are thought to have been influenced by training and continued monitoring of the image acquisition process at the Field Centers and analysis at the Echo RC.

Standard echocardiography

LV mass assessment showed the highest intra-class correlation coefficient, showing a strong consistency as previously described in the literature.[12] In our study, however, the highest technical errors in standard 2D and M-mode parameters were found for M-mode-derived LV mass. The calculation of LV mass by M-mode requires geometric assumptions of the heart, describing a 3D model based on linear measurements. This calculation requires cubing the values acquired from M-mode linear measurements, therefore magnifying the variation between readings.[10, 13]

In our study, LV mass had a higher variation compared to aortic root and LA diameter. The coefficients of variation values were consistent with previous CARDIA examinations. In the CARDIA Y5 exam, technical errors for components of variability for LV mass measurements were 10% for both intra- and inter-sonographer performance, 8% for intra-reader, and 14% for inter-reader.[9] In CARDIA Year-10, similar quality control measures granted coefficients of variation for measurement of LV mass of 10.6% for inter-reader, 9.5% for intra-reader, 13.5% for intra-sonographer, and 10% for inter-sonographer.[14] In the Cardiovascular Health Study, M-mode LV mass had 10% variation between measurements (11% due to septal thickness, 4% LV dimension, and 8% posterior wall thickness) compared to 8% for LA dimension.[15] Values of technical errors in M-mode LV mass should be related to the inherent measurements challenges and the fact that the myocardial mass is derived from a formula that computes three different cubed measurements, increasing the source errors.[13] In contrast, aortic root and LA dimension derive from a single linear measurement, [10] with high reproducibility profile even in a small center with low volume of patients.[16] Low variation and high correlation has also been reported for measurements of carotid intima-media thickness, also assessed by linear measurements, with ICC ranging from 0.79 to 0.98 and coefficient of variation ranging from 3.3% to 4.6%.[17]

Assessing LV ejection fraction is an important parameter of quality of care, but variability of the echocardiography-derived assessment is a concern.[18, 19] For the 2-dimensional echocardiography parameters, the coefficient of variation for LVEDV was higher in our study compared to LVEF. These results are similar to the literature. Himelman et al.

assessed 3 normal subjects, producing 30 studies and 90 readings. The authors reported an inter-scan mean variability of 5% for LVEF and 10% for LVEDV; as well as inter-reader variability of 7% for LVEF and 19% for LVEDV.[20] Other studies reported inter-observer variation of 23% for LVEDV and 12% to 43% for LVEF.[21-23] However, ICC provides a more robust assessment of reproducibility, showing lower values for LVEF compared to LVEDV. This can be partially explained by the fact that, for computing LVEF, two volume measurements are needed (end-systolic and end-diastolic volumes), therefore increasing the possibility of measurement error.

Speckle tracking echocardiography

Cardiac deformation has long been assessed by magnetic resonance with high accuracy.[24, 25] STE is a novel method to assess cardiac deformation by ultra-sound, more sensitive and sophisticated to identify early abnormalities than traditional echocardiography parameters can.[26] As a relatively novel technique, there are still technical challenges for image acquisition.[27] In our study, averaging at least 3 LV segments seems adequate for STE parameters.

STE techniques have shown a robust profile for accuracy and reproducibility in the literature.[28, 29] The HUNT study enrolled 1,266 healthy European individuals to study the distribution of longitudinal systolic strain and strain rate. During the study, 10 European healthy volunteers were recruited to be scanned by two different echocardiographers; the images were analyzed twice for longitudinal deformation by both professionals. For global end-systolic global strain, the coefficient of repeatability was $\pm 2\%$ strain for the inter-reader analyses, and coefficients of variation were between 3% and 4%.[30] In our study, 40 images were read twice by all 4 readers to assess reproducibility (320 analyses) of longitudinal, radial, and circumferential deformation. Robust inter- and intra-reproducibility profiles were found for all STE parameters, with longitudinal strain being most reproducible.

The consistency of STE measurement by multi-site sonographers in a large cohort has not been assessed before. Our results for FC sonographers indicate that STE readings, particularly longitudinal peak strain, can be reliably performed at the moment of image acquisition, after minimum STE-specific sonographer training. Training and re-training appears to improve quality of measurements in the Field Centers. Thus, large longitudinal studies may use STE to accurately assess cardiac function with appropriate training.

We have shown quality control measures used in echocardiography acquisition and interpretation in the CARDIA Y25 examination. From the images acquired by Field Center sonographers, a robust inter-scan reproducibility of echocardiography measurements was found both within and between professionals. Moreover, robust reproducibility results were found for echocardiography analyzes in the CARDIA Core Imaging Laboratory, including 2D, M-mode, and STE imaging. We particularly show that STE can provide reliable information for large cohort studies. Consistent quality control may increase the reliability of echocardiography measurements in large cohort studies conducted over a long period of time. These results may inform strategies to implement quality improvement processes in clinical echocardiography laboratories to allow STE to be incorporated into clinical care.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors thank the other investigators, the staff, and the participants of the CARDIA study for their valuable contributions.

Funding: This study was funded by the National Institutes of Health (grant number HC-95241). Dr. Armstrong was funded by Universidade Federal do Vale do São Francisco and by the Johns Hopkins University.

References

1. Carlson MD, Morrison RS. Study design, precision, and validity in observational studies. *J Palliat Med.* 2009; 12:77–82. [PubMed: 19284267]
2. Proceedings of “Methods for Longitudinal Data Analysis in Epidemiological and Clinical Studies”. Workshop sponsored by the National Heart, Lung, and Blood Institute. Bethesda, Maryland, 25–26 September, 1986. *Stat Med.* 1988; 7:1–361. [PubMed: 3353599]
3. Picard MH, Adams D, Bierig SM, et al. American Society of Echocardiography recommendations for quality echocardiography laboratory operations. *J Am Soc Echocardiogr.* 2011; 24:1–10. [PubMed: 21172594]
4. von Elm E, Altman DG, Egger M, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancet.* 2007; 370:1453–1457. [PubMed: 18064739]
5. Cobo E, Cortes J, Ribera JM, et al. Effect of using reporting guidelines during peer review on quality of final manuscripts submitted to a biomedical journal: masked randomised trial. *BMJ.* 2011; 343:d6783. [PubMed: 22108262]
6. Goh V, Schaeffter T, Leach M. Reproducibility of dynamic contrast-enhanced MR imaging: why we should care. *Radiology.* 2013; 266:698–700. [PubMed: 23431225]
7. Friedman GD, Cutter GR, Donahue RP, et al. CARDIA: study design, recruitment, and some characteristics of the examined subjects. *J Clin Epidemiol.* 1988; 41:1105–1116. [PubMed: 3204420]
8. Maron BJ, Gardin JM, Flack JM, et al. Prevalence of hypertrophic cardiomyopathy in a general population of young adults. Echocardiographic analysis of 4111 subjects in the CARDIA Study Coronary Artery Risk Development in (Young) Adults. *Circulation.* 1995; 92:785–789. [PubMed: 7641357]
9. Gardin JM, Wagenknecht LE, Anton-Culver H, et al. Relationship of cardiovascular risk factors to echocardiographic left ventricular mass in healthy young black and white adult men and women. The CARDIA study Coronary Artery Risk Development in Young Adults. *Circulation.* 1995; 92:380–387. [PubMed: 7634452]
10. Lang RM, Bierig M, Devereux RB, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. *J Am Soc Echocardiogr.* 2005; 18:1440–1463. [PubMed: 16376782]
11. Nagueh SF, Appleton CP, Gillebert TC, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. *J Am Soc Echocardiogr.* 2009; 22:107–133. [PubMed: 19187853]
12. Armstrong AC, Gjesdal O, Almeida A, et al. Left ventricular mass and hypertrophy by echocardiography and cardiac magnetic resonance: the multi-ethnic study of atherosclerosis. *Echocardiography.* 2014; 31:12–20. [PubMed: 23930739]
13. Armstrong AC, Gjesdal O, Wu C, et al. Left ventricular mass assessed by Echocardiography and Cardiac Magnetic Resonance, cardiovascular outcomes, and medical practice. *J Am Coll Cardiol Img.* 2012; 5:11.

14. Gardin JM, Brunner D, Schreiner PJ, et al. Demographics and correlates of five-year change in echocardiographic left ventricular mass in young black and white adult men and women: the Coronary Artery Risk Development in Young Adults (CARDIA) study. *J Am Coll Cardiol.* 2002; 40:529–535. [PubMed: 12142122]
15. Gardin JM, Wong ND, Bommer W, et al. Echocardiographic design of a multicenter investigation of free-living elderly subjects: the Cardiovascular Health Study. *J Am Soc Echocardiogr.* 1992; 5:63–72. [PubMed: 1739473]
16. Ogah OS, Adebajo AT, Otukoya AS, et al. Echocardiography in Nigeria: use, problems, reproducibility and potentials. *Cardiovasc Ultrasound.* 2006; 4:13. [PubMed: 16551364]
17. Gonzalez J, Wood JC, Dorey FJ, et al. Reproducibility of carotid intima-media thickness measurements in young adults. *Radiology.* 2008; 247:465–471. [PubMed: 18349312]
18. Miller AL, Dib C, Li L, et al. Left ventricular ejection fraction assessment among patients with acute myocardial infarction and its association with hospital quality of care and evidence-based therapy use. *Circ Cardiovasc Qual Outcomes.* 2012; 5:662–671. [PubMed: 22949495]
19. Wood PW, Choy JB, Nanda NC, et al. Left ventricular ejection fraction and volumes: it depends on the imaging method. *Echocardiography.* 2014; 31:87–100. [PubMed: 24786629]
20. Himelman RB, Cassidy MM, Landzberg JS, et al. Reproducibility of quantitative two-dimensional echocardiography. *Am Heart J.* 1988; 115:425–431. [PubMed: 3341178]
21. Reichek N, Helak J, Plappert T, et al. Anatomic validation of left ventricular mass estimates from clinical two-dimensional echocardiography: initial results. *Circulation.* 1983; 67:348–352. [PubMed: 6848224]
22. Tortoledo FA, Quinones MA, Fernandez GC, et al. Quantification of left ventricular volumes by two-dimensional echocardiography: a simplified and accurate approach. *Circulation.* 1983; 67:579–584. [PubMed: 6821900]
23. Gordon EP, Schnittger I, Fitzgerald PJ, et al. Reproducibility of left ventricular volumes by two-dimensional echocardiography. *J Am Coll Cardiol.* 1983; 2:506–513. [PubMed: 6875114]
24. Young AA, Axel L, Dougherty L, et al. Validation of tagging with MR imaging to estimate material deformation. *Radiology.* 1993; 188:101–108. [PubMed: 8511281]
25. Garot J, Lima JA, Gerber BL, et al. Spatially resolved imaging of myocardial function with strain-encoded MR: comparison with delayed contrast-enhanced MR imaging after myocardial infarction. *Radiology.* 2004; 233:596–602. [PubMed: 15516622]
26. Geyer H, Caracciolo G, Abe H, et al. Assessment of myocardial mechanics using speckle tracking echocardiography: fundamentals and clinical applications. *J Am Soc Echocardiogr.* 2010; 23:351–369. quiz 453–355. [PubMed: 20362924]
27. Spriestersbach H, Oh-Ici D, Schmitt B, et al. The Influence of the Region of Interest Width on Two-Dimensional Speckle Tracking-Based Measurements of Strain and Strain Rate. *Echocardiography.* 2014
28. Singh GK, Cupps B, Pasque M, et al. Accuracy and reproducibility of strain by speckle tracking in pediatric subjects with normal heart and single ventricular physiology: a two-dimensional speckle-tracking echocardiography and magnetic resonance imaging correlative study. *J Am Soc Echocardiogr.* 2010; 23:1143–1152. [PubMed: 20850945]
29. Kimura K, Takenaka K, Ebihara A, et al. Reproducibility and diagnostic accuracy of three-layer speckle tracking echocardiography in a swine chronic ischemia model. *Echocardiography.* 2011; 28:1148–1155. [PubMed: 21967399]
30. Dalen H, Thorstensen A, Aase SA, et al. Segmental and global longitudinal strain and strain rate based on echocardiography of 1266 healthy individuals: the HUNT study in Norway. *Eur J Echocardiogr.* 2010; 11:176–183. [PubMed: 19946115]

Abbreviation List

2D	2-dimensional
ASE	American Society of Echocardiography

BMI	body-mass index
CARDIA	Coronary Artery Risk Development in Young Adults
Echo RC	Echocardiography Reading Center
FC	Field Center
ICC	intra-class correlation coefficient
LA	left atrial
LV	left ventricular
LVEDV	LV end-diastolic volume
LVEF	LV ejection fraction
STE	speckle tracking echocardiography

Figure 1. Number of properly tracking left ventricular segments during Speckle Tracking Echocardiography (STE) analysis in the CARDIA study, according to acoustic view (3,068 participants)

Table I
Description of Echocardiography parameters in the Year-25 CARDIA examination,
according to image quality

Image Quality	Number of Participants	Percentage (%)	Mean	SD
<i>2D echo LVEDV (mL)</i>				
Poor	76	2	110.24	35.37
Fair	1,186	37	111.79	29.81
Good	1,521	47	111.71	30.06
Excellent	439	14	113.67	32.27
<i>Overall</i>	3,222	100	111.97	30.40
<i>2D echo LVEF (%)</i>				
Poor	75	2	62.46	6.97
Fair	1,186	37	60.09	6.87
Good	1,521	47	61.51	7.16
Excellent	439	14	63.92	7.66
<i>Overall</i>	3,221	100	61.34	7.23
<i>M-mode echo Aortic root (cm)</i>				
Poor	309	9	3.26	0.47
Fair	1,023	30	3.11	0.41
Good	1,744	51	3.02	0.42
Excellent	340	10	3.03	0.38
<i>Overall</i>	3,416	100	3.07	0.42
<i>M-mode echo LA diameter (cm)</i>				
Poor	306	9	3.86	0.54
Fair	1,009	30	3.73	0.49
Good	1,721	51	3.67	0.50
Excellent	338	10	3.71	0.48
<i>Overall</i>	3,374	100	3.71	0.50
<i>M-mode echo LV mass (g)</i>				
Poor	87	3	198.63	60.22
Fair	958	31	168.62	54.57
Good	1,738	56	164.83	50.28
Excellent	339	11	175.09	52.66
<i>Overall</i>	3,122	100	168.05	52.51

Legend: LVEDV: 2D left ventricular end-diastolic volume (4-chamber view); LVEF: 2D left ventricular ejection fraction (4-chamber view); Ao Root: M-mode aorta root diameter; LA diameter: M-mode left atrial dimension; LV mass: M-mode left ventricular mass.

Inter- and intra-sonographer reproducibility for M-mode and 2-D measurements in repeated echocardiography scans* in the CARDIA Y25 exam

Table II

Reproducibility assessment					
<i>Inter-sonographer reproducibility (n = 42)</i>					
	LVEDV	LVEF	Ao Root	LAD	LV mass
Coefficient of Variation, %	10.6	5.8	5.9	7.3	11.8
<i>Intra-sonographer reproducibility (n = 46)</i>					
	LVEDV	LVEF	Ao Root	LAD	LV mass
Coefficient of Variation, %	11.2	5.1	5.3	6.0	10.3
<i>All-sonographer reproducibility (n = 88)</i>					
	LVEDV	LVEF	Ao Root	LAD	LV mass
Intra-class correlation	0.80	0.58	0.81	0.73	0.91

Legend: LVEDV: 2D left ventricular end-diastolic volume; LVEF: 2D left ventricular ejection fraction; Ao Root: M-mode aorta root diameter; LAD: M-mode left atrial anterior-posterior diameter; LV mass: M-mode left ventricular mass.

* Mean interval between scans was 20 days.

Table III
Inter- and intra-reader reproducibility in the re-assessment of the same M-mode and 2-D echocardiography images in the CARDIA Y25 exam

Reproducibility assessment					
Inter-reader reproducibility (n = 200)					
	LVEDV	LVEF	Ao Root	LAD	LV mass
Coefficient of Variation, %	9.8	7.7	5.6	6.4	11.3
Intra-class correlation	0.87	0.59	0.82	0.80	0.87
Intra-reader reproducibility (n = 40)					
	LVEDV	LVEF	Ao Root	LAD	LV mass
Coefficient of Variation, %	8.9	6.1	4.1	5.9	11.5
Intra-class correlation	0.84	0.76	0.86	0.79	0.80

Legend: LVEDV: 2D left ventricular end-diastolic volume; LVEF: 2D left ventricular ejection fraction; Ao Root: M-mode aorta root diameter; LAD: M-mode left atrial anterior-posterior diameter; LV mass: M-mode left ventricular mass.

Table IV
Left ventricular speckle tracking echocardiography deformation parameters, according to acoustic view and number of properly tracking segments (n =3,068)

Acoustic view / Number of tracking segments	Number of Participants	Mean	SD	CV
<i>4-chamber longitudinal strain (%)</i>				
6	1,996	-14.36	2.31	-0.16
5	659	-14.53	2.54	-0.18
4	316	-14.90	3.22	-0.22
3	62	-14.72	3.60	-0.24
<i>2-chamber longitudinal strain (%)</i>				
6	1,236	-14.89	2.46	-0.16
5	579	-15.19	2.77	-0.18
4	354	-15.79	3.14	-0.20
3	62	-15.96	3.66	-0.23
<i>Circumferential strain (%)</i>				
6	2,115	-14.52	2.90	-0.20
5	582	-14.12	3.02	-0.21
4	337	-14.66	3.36	-0.23
3	57	-15.74	4.33	-0.27
<i>Radial strain (%)</i>				
6	2,115	36.22	12.16	0.34
5	582	34.10	13.62	0.40
4	337	32.87	13.44	0.41
3	57	34.55	17.92	0.52

Legend: SD – standard deviation; CV – coefficient of variation

Table V
Inter- and intra-reader reproducibility in the re-assessment of the same Speckle Tracking
Echocardiography images in the CARDIA Y25 exam

Reproducibility assessment				
Inter-reader reproducibility (n = 40)				
	4-ch Ell	2-ch Ell	Ecc	Err
Coefficient of variation, %	10.4	10.7	12.9	15.3
Intra-class correlation	0.55	0.71	0.67	0.84
Intra-reader reproducibility (n = 160)				
	4-ch Ell	2-ch Ell	Ecc	Err
Coefficient of variation, %	6.6	5.5	6.8	12.1
Intra-class correlation	0.79	0.87	0.81	0.89

Legend: 4-ch – 4-chamber; Ell– peak longitudinal strain; 2-ch – 2-chamber; Ecc – peak circumferential strain; Err – peak radial strain.