Comparison of Local Sine Wave Modeling With Harmonic Phase Analysis for the Assessment of Myocardial Strain

Christopher A. Miller, MBChB,1–3* Alex Borg, MD,1 David Clark, BSc,4 Christopher D. Steadman, MBChB,5,6 Gerry P. McCann, MD,5,6 Patrick Clarysse, PhD,7 Pierre Croisille, MD, PhD,7,8 and Matthias Schmitt, MD, PhD1,2

Purpose: To compare local sine-wave modeling (SinMod) with harmonic phase analysis (HARP), for assessment of left ventricular (LV) circumferential strain (εcc) from tagged cardiovascular magnetic resonance images.

Materials and Methods: Mid-ventricular spatial modulation of magnetization was performed in 60 participants (15 each with hypertrophic, dilated or ischemic cardiomyopathy and 15 healthy controls) at 1.5 Tesla. Global and segmental peak transmural εcc were measured using HARP and SinMod. Repeated measurements were performed on 25% of examinations to assess observer variability. Effect of contrast was assessed in 10 additional patients.

Results: SinMod showed a high level of agreement with HARP for global εcc (mean difference −0.02, 95% limits of agreement −6.46 to 6.43%). Agreement was much lower for segmental εcc. Both methods showed excellent observer agreement for global εcc (intra-class correlation coefficient >0.75). Observer agreement for segmental εcc was also excellent with SinMod, but was significantly lower with HARP. Analysis time was significantly shorter using SinMod. Pre- and postcontrast εcc measurements were not significantly different using either technique, although postcontrast measurements showed greater variability with HARP.

Conclusion: SinMod and HARP-based measurements of global εcc have a high level of agreement, but segmental agreement is substantially lower. SinMod has generally lower observer variability, is faster and is less affected by contrast, but requires further validation.

Key Words: cardiovascular magnetic resonance; myocardial strain; local sine-wave modeling; harmonic phase analysis; cardiomyopathy


SUBTLE VARIATIONS IN the timing and magnitude of regional myocardial deformation exist in healthy hearts (1,2). Such variations become more pronounced in myocardial disease and assessment of regional ventricular deformation has proved to be more sensitive than ejection fraction (EF) for detecting myocardial dysfunction. Indeed a decline in myocardial strain is seen to precede a decline in EF in a range of cardiomyopathies (3–8), and alterations in myocardial strain parameters have been described in asymptomatic individuals with sub-clinical atherosclerosis, as well as asymptomatic gene carriers of hypertrophic cardiomyopathy and skeletal myopathies, despite normal left ventricular (LV) mass, volume indices and EF (9–11).

Cardiovascular magnetic resonance (CMR) assessment of myocardial deformation has been validated with sonomicrometry (12) and, owing to its high reproducibility, is considered the gold-standard modality for noninvasive assessment of strain (13). CMR-based strain assessment is most commonly performed using spatial modulation of magnetization (SPAMM) (14) or complementary spatial modulation of magnetization (CSPAMM) (15) sequences, in which selective radiofrequency saturation pulses generate, for example, a grid-pattern of dark bands perpendicular to
the image plane before image acquisition ("tagging," Fig. 1). The bands deform with the myocardium during the cardiac cycle and this deformation can be tracked, allowing assessment of strain.

Quantification of strain from tagged images has been greatly facilitated by advances in image processing software. Harmonic phase (HARP) analysis is currently the most widely used method, the accuracy of which has been validated in animal and human studies (16–18). HARP analysis uses the distinct spectral peaks seen in the Fourier domain of tagged CMR images. The inverse Fourier transform of the first harmonic of these spectral peaks, extracted by a bandpass filter, yields harmonic magnitude and phase images. Cardiac displacement can be calculated from the phase changes between successive images. However, potential errors in calculated deformation can occur due to image degradation, particularly later in the cardiac cycle.

Local sine-wave modeling (SinMod) is an alternative method of quantifying strain from tagged CMR images (19). The SinMod method estimates dense displacement fields, which are used to compute strain. Signal intensity distribution in the local environment of each pixel is modeled as a sine-wave with local frequency and amplitude, selected using a tuned bandpass filter. The quotient of phase difference and average frequency for each pixel on two successive images yields an estimate of local displacement. As part of the SinMod algorithm, the quality of the local sine-wave model is assessed and if it is low, motion is estimated by averaging over a larger environment. As such, SinMod appears to be less sensitive to noise than HARP (19).

The aim of this study was to compare SinMod with HARP for the assessment of Lagrangian LV peak systolic circumferential strain ($e_{cc}$) in patients with a range of global and regional myocardial diseases, and healthy controls. Observer variability and the effect of gadolinium contrast were also assessed.

MATERIALS AND METHODS

Study Design

Fifteen consecutive patients with each of the following cardiomyopathies, undergoing clinically indicated CMR scanning, were recruited: hypertrophic cardiomyopathy (HCM), dilated cardiomyopathy (DCM), and ischemic cardiomyopathy (ICM) (45 patients in total). Fifteen healthy volunteers with no history of cardiovascular disease were also included. All participants gave written informed consent.

Image Acquisition

Participants underwent CMR imaging using a 1.5 Tesla (T) scanner (Avanto; Siemens Medical Imaging, Germany) with a 32-element phased-array coil. Steady-state free precession (SSFP) end-expiratory breathhold cines with retrospective gating were acquired in multiple planes, including contiguous short-axis images from the atrioventricular ring to the apex. Short-axis tagged images were acquired at midventricular level (located midway between the atrioventricular ring and apex, planned from the long-axis SSFP images) using an electrocardiogram-triggered segmented k-space fast gradient echo sequence with

Figure 1. Steady-state free precession mid-ventricular short-axis images in diastole (a) and systole (b) and corresponding spatial modulation of magnetization tagged images (c,d) in a patient with hypertrophic cardiomyopathy.
spatial modulation of magnetization in orthogonal planes, with the following parameters: slice thickness: 7 mm; grid tag spacing: 7 mm; repetition time (TR): 33 ms; echo time (TE): 4 ms; flip angle: 12°; typical spatial resolution: 1.8 × 1.3 × 7 mm; segments: 7, temporal resolution: 30–50 ms (Fig. 1). Images were acquired during a single breath hold and before contrast administration.

**Image Analysis**

Peak systolic $\epsilon_{cc}$ was measured from the mid-ventricular short-axis tagged images using the HARP (Diagnosoft®, USA, v2.7) and SinMod (inTag®, v1.0, CREATIS lab, France, and Maastricht University, The Netherlands, run as a plug-in for OsirIX Imaging Software, Pixmeo, Switzerland, v3.8) methods.

HARP analysis involved the following steps: (i) confirmation of appropriate k-space setup; (ii) defining the region of interest; (iii) manual endocardial and epicardial border tracing in a frame selected by the user for optimal myocardial-blood contrast, to create a “mesh” which automatically propagated to each frame; (iv) identification of the anterior right ventricular septal insertion point, on the basis of which the mesh was divided into six segments: anterior, anteroseptal, inferoseptal, inferior, inferolateral, and anterolateral; (v) manual adjustment of contours to ensure that the mesh remained within the myocardium. $\epsilon_{cc}$ values were then calculated by the software for each frame (Fig. 2).

SinMod analysis involved the following steps: (i) specifying tag spacing used (7 mm); (ii) defining the region of interest; (iii) manual endocardial and epicardial border tracing in the end-systolic frame which was then automatically propagated to each frame; (iv) identification of the anterior right ventricular septal insertion point, on the basis of which the mesh was divided into six segments; anterior, anteroseptal, inferoseptal, inferior, inferolateral, and anterolateral. $\epsilon_{cc}$ values were then calculated by the software for each frame (Fig. 3).

By convention, systolic $\epsilon_{cc}$ was denoted as negative, indicative of shortening in the circumferential direction. Peak systolic $\epsilon_{cc}$ was determined as most negative systolic value. Analysis was performed on the
entire mid-ventricular short-axis slice (global analysis), and on each of the six segments (segmental analysis). Pooled segmental analysis was performed by summing the peak systolic circumferential strain (e\text{cc}) values in each segment and then taking the average. Analysis time for both techniques was recorded.

LV volume indices and EF were measured from the contiguous short-axis SSFP images using Argus Syngo MR software version 27A (Siemens Medical Imaging, Germany).

**Observer Variability**

To assess interobserver variability, 15 randomly selected scans (25%) were independently re-analyzed by a second observer. To assess intraobserver variability, 15 randomly selected scans (25%) were re-analyzed by the first observer with a 1-month temporal separation between analyses.

**Effect of Gadolinium Contrast on e\text{cc}**

To assess the effect of gadolinium contrast on peak systolic e\text{cc} measurements, 10 additional, randomly selected patients referred for clinically indicated CMR were enrolled subsequent to the cohort described above. This group included five patients with structurally normal hearts: two with HCM and three with DCM. Tagged images of the same mid-ventricular short-axis slice were obtained before and after contrast injection (mean 17 min postcontrast; range, 11–22 min) and analyzed with the HARP and SinMod methods by a single observer.

**Statistics**

Values are expressed as mean ± standard deviation (SD) unless stated otherwise. Agreement between each method was evaluated using Bland-Altman testing by calculating mean difference (bias) and 95% limits of agreement (i.e., mean difference ± 2 SD). Correlation was assessed using Spearman’s rank correlation coefficient. Sub-group analysis was performed to assess the agreement between HARP and SinMod according to ejection fraction (EF < 55% and EF ≥ 55%), end diastolic volume (body surface area-indexed end diastolic volume (EDV) < 90 mL/m² and ≥ 90 mL/m²) and pattern of myocardial dysfunction.

**Figure 3.** Local sine-wave modeling (SinMod) analysis method in the same patient with hypertrophic cardiomyopathy as in Figure 2. SinMod analysis involved defining a region of interest (a), manual endo- and epicardial border tracing in a single frame, followed by automated propagation of the contours to all other frames (b, displayed at end-systole). Peak systolic circumferential strain (e\text{cc}) values were then automatically calculated and displayed both as strain maps (c, displayed at end-systole; color corresponds to regional strain value according to scale on left) and graphically (d; x-axis = frame count; y-axis = e\text{cc} [decimal]; colored lines correspond to myocardial segments according to diagram in bottom right corner). In this case, the anteroseptal segment had reduced peak systolic e\text{cc} compared with other segments.
(global [DCM group] and regional [ICM group]). Inter- and intraobserver agreement were evaluated using intraclass correlation coefficient (ICC) (20–22). In keeping with other studies, agreement was considered as poor when ICC was < 0.4, fair 0.40–0.59, good 0.60–0.74 and excellent ≥ 0.75 (23). Inter- and intraobserver variability are also displayed graphically, calculated as 1–ICC (24). The significance of the differences in variability was assessed using a Wilcoxon rank comparison of the squared differences (25). P-values < 0.05 were considered significant. Statistical analysis was performed using SPSS Statistics (version 19, IBM).

RESULTS

Patient characteristics are displayed in Table 1. Patients exhibited a wide range of end-diastolic, and end-systolic volumes and EF.

Comparison of HARP and SinMod Analysis

There was a high level of agreement between HARP and SinMod for measurement of global peak systolic \( \varepsilon_{cc} \) (Tables 2, 3, Fig. 4). Both techniques found global peak systolic \( \varepsilon_{cc} \) to be reduced in each of the cardiomyopathies compared with healthy controls, although using HARP, the difference between patients with HCM and healthy controls showed only a strong trend toward being significant (Fig. 5).

There was substantially lower agreement between HARP and SinMod for segmental peak systolic \( \varepsilon_{cc} \) measurements, suggesting the two techniques were not interchangeable for segmental analysis (Tables 2, 3, Fig. 6). Agreement was lowest in the lateral segments.

Analysis time using SinMod was significantly shorter than for HARP (84 ± 42 versus 201 ± 120 s, \( P = 0.02 \)). The difference was mainly due to the manual adjustment of endo- and epicardial contours required with HARP to ensure that the mesh remained within the myocardium.

Subgroup Analysis

Agreement between HARP and SinMod for measurement of global peak systolic \( \varepsilon_{cc} \) according to EF, EDV and pattern of myocardial dysfunction is displayed in Table 4. Agreement remained high across all subgroups, but was minimally higher in patients with EF ≥ 55% compared with patients with EF < 55%, and in patients with body surface area-indexed EDV < 90 mL/m² compared with those with EDV ≥ 90 mL/m². Agreement was higher in those with patients with global dysfunction compared with those with regional dysfunction.

Variability

Both methods showed excellent interobserver agreement for measurement of global peak systolic \( \varepsilon_{cc} \) (HARP ICC 0.84, SinMod ICC 0.93; Fig. 7). Both methods also showed excellent intraobserver agreement for measurement of global peak systolic \( \varepsilon_{cc} \), although intraobserver agreement was significantly higher with SinMod than with HARP (SinMod ICC 0.93 versus HARP ICC 0.84; \( P = 0.01 \)).

Both analysis techniques showed greater variability for segmental peak systolic \( \varepsilon_{cc} \) measurements than for global measurements. However, segmental inter- and intraobserver agreement remained excellent with SinMod (ICC ≥ 0.75) in all but one segment (Fig. 7). SinMod had significantly higher observer agreement than HARP for pooled segmental peak systolic \( \varepsilon_{cc} \) measurements (interobserver agreement: SinMod ICC 0.87 versus HARP ICC 0.69, \( P < 0.0005 \); intraobserver agreement: SinMod ICC 0.84 versus HARP ICC 0.68, \( P < 0.0005 \)).

Effect of Gadolinium Contrast

There were no significant differences between pre- and postcontrast global peak systolic \( \varepsilon_{cc} \) measurements using HARP (mean global precontrast \( \varepsilon_{cc} \) –14.19 ± 4.33%, mean global postcontrast \( \varepsilon_{cc} \) –14.78 ± 4.39%; mean difference 0.59%; \( P = 0.44 \), i.e., not significant), or using SinMod (mean global precontrast \( \varepsilon_{cc} \) –14.67 ± 4.34%, mean global post-contrast \( \varepsilon_{cc} \) –14.84 ± 5.00%; mean difference 0.17%; \( P = 0.65 \)). There were also no significant differences between pre- and postcontrast pooled segmental peak systolic \( \varepsilon_{cc} \) measurements using HARP (mean segmental precontrast \( \varepsilon_{cc} \) –15.60 ± 4.50%, mean segmental postcontrast \( \varepsilon_{cc} \) –15.00 ± 5.54%; mean difference –0.60% \( P = 0.41 \)), or using SinMod (mean segmental precontrast \( \varepsilon_{cc} \) –16.22 ± 5.75%, mean segmental postcontrast \( \varepsilon_{cc} \) –16.36 ± 6.24%; mean difference –0.14% \( P = 0.49 \)).

The 95% limits of agreement between pre- and postcontrast peak systolic \( \varepsilon_{cc} \) measurements using SinMod (global –1.56 to 2.39%; segmental –5.94 to 6.21%) were within the precontrast intraobserver 95% limits of agreement (global –4.00 to 2.05%; segmental...
### Table 2: Measurements Using Harmonic Phase (HARP) and Local Sine-Wave Modeling (SinMod) Analysis Methods

<table>
<thead>
<tr>
<th>Region</th>
<th>HARP Mean ± SD</th>
<th>SinMod Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>13.82 ± 5.01</td>
<td>13.66 ± 4.97</td>
</tr>
<tr>
<td>DCM</td>
<td>17.71 ± 6.57</td>
<td>17.61 ± 4.97</td>
</tr>
<tr>
<td>HCM</td>
<td>18.79 ± 6.08</td>
<td>18.64 ± 5.77</td>
</tr>
<tr>
<td>Pooled segments</td>
<td>15.88 ± 5.65</td>
<td>15.52 ± 4.97</td>
</tr>
<tr>
<td>Anterolateral</td>
<td>19.14 ± 6.47</td>
<td>18.94 ± 6.08</td>
</tr>
<tr>
<td>Inferolateral</td>
<td>16.49 ± 5.56</td>
<td>16.22 ± 4.96</td>
</tr>
<tr>
<td>Inferior</td>
<td>14.79 ± 5.56</td>
<td>14.22 ± 4.69</td>
</tr>
<tr>
<td>Anteroseptal</td>
<td>13.82 ± 5.01</td>
<td>13.75 ± 5.16</td>
</tr>
<tr>
<td>Inferoseptal</td>
<td>13.21 ± 5.01</td>
<td>13.70 ± 4.95</td>
</tr>
</tbody>
</table>

**Note:** Values represent the mean ± standard deviation.}

**DISCUSSION**

This is the first in vivo study to assess the level of agreement between the SinMod method of myocardial strain analysis and the more established HARP method. It also represents the first clinical evaluation of the observer variability of SinMod and is the first study to assess observer variability of HARP in patients with cardiovascular disease. Furthermore, it represents the first assessment of the effect of gadolinium contrast on these analysis techniques.

The current study included healthy volunteers and patients with a variety of cardiomyopathies in order to assess agreement between the two analysis techniques across a range of LV size, and across a range of global and regional myocardial dysfunction. Despite the differences in methodology, SinMod showed a high level of agreement with HARP for measurement of global mid-ventricular LV peak systolic strain (Scc), which was maintained across EF, EDV and pattern of myocardial dysfunction sub-groups. Segmental agreement between methods was much lower, which may reflect variability in methods of contour tracing, which would be expected to have a proportionally greater effect on segmental analysis compared with global analysis, and variability in right ventricular insertion point identification, rather than true calculated differences in regional strain values. In addition, the inherent spacing between the grid tags (7 mm in the current study, in keeping with the Multi-Ethnic Study of Atherosclerosis) (9,23,26), which is a recognized limitation of the tagging technique, is likely to explain why agreement between the two analysis methods was lowest in the lateral segments, i.e., where the LV wall is thinnest. Analysis was rapid with both techniques, although faster with SinMod, indeed with a mean analysis time of around 90 seconds. SinMod is clinically feasible.

Both methods showed high reproducibility (ICC > 0.75) for measurement of global peak systolic strain (Scc). The pooled segmental reproducibility of HARP in this study (interobserver ICC 0.69, intraobserver ICC 0.68) was lower than in the study by Castillo et al (23) (interobserver ICC ranged between 0.74 and 0.84 depending on image quality, intraobserver ICC 0.79–0.89). However, the current study included patients with a variety of cardiac pathologies where as Castillo et al included only asymptomatic volunteers free from clinical cardiovascular disease. The reproducibility of
SinMod for pooled segmental analysis (interobserver ICC 0.87, intraobserver ICC 0.84) was significantly higher than for HARP in the current study and compared favorably with the reproducibility of HARP in the study by Castillo et al. The higher reproducibility of SinMod may be due to this method being less sensitive to noise in the tagged images. Also, the automated propagation of endo- and epicardial contours between frames, and hence the endo- and epicardial border tracking through the cardiac cycle, visually appeared more consistent using the SinMod technique than with HARP; however, this was not assessed quantitatively.

The $\varepsilon_{cc}$ values in healthy subjects in the current study are in close agreement with those found by Fernandes et al. (9) using the HARP analysis technique, with the same regional variation, i.e., highest (most

### Table 3

<table>
<thead>
<tr>
<th>HARP – SinMod</th>
<th>Mean difference ±SD (%)</th>
<th>95% limits of agreement (%)</th>
<th>Correlation coefficient ($\rho$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>$-0.02 \pm 3.29%$</td>
<td>$-6.46 \text{ to } 6.43%$</td>
<td>0.82</td>
</tr>
<tr>
<td>Anterior</td>
<td>$-1.30 \pm 6.08%$</td>
<td>$-13.22 \text{ to } 10.61%$</td>
<td>0.59</td>
</tr>
<tr>
<td>Anterolateral</td>
<td>$-2.46 \pm 7.98%$</td>
<td>$-18.10 \text{ to } 13.19%$</td>
<td>0.28</td>
</tr>
<tr>
<td>Inferolateral</td>
<td>$1.13 \pm 7.49%$</td>
<td>$-13.56 \text{ to } 15.81%$</td>
<td>0.34</td>
</tr>
<tr>
<td>Inferior</td>
<td>$-0.71 \pm 6.23%$</td>
<td>$-12.93 \text{ to } 11.51%$</td>
<td>0.46</td>
</tr>
<tr>
<td>Inferoseptal</td>
<td>$-0.69 \pm 4.77%$</td>
<td>$-10.03 \text{ to } 8.65%$</td>
<td>0.64</td>
</tr>
<tr>
<td>Anteroseptal</td>
<td>$-0.69 \pm 6.61%$</td>
<td>$-13.65 \text{ to } 12.27%$</td>
<td>0.56</td>
</tr>
<tr>
<td>Pooled segments</td>
<td>$-0.82 \pm 6.66%$</td>
<td>$-13.87 \text{ to } 12.24%$</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Mean difference (SD), Bland-Altman 95% limits of agreement and correlation coefficient for the comparison of HARP and SinMod.

Figure 5. Global peak systolic circumferential strain ($\varepsilon_{cc}$) in healthy controls, hypertrophic cardiomyopathy (HCM), dilated cardiomyopathy (DCM) and ischemic cardiomyopathy (ICM) groups. Bars represent mean strain value ±SD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 6. Agreement between local sine-wave modeling (SinMod) and harmonic phase (HARP) analysis methods for pooled segmental peak systolic circumferential strain ($\varepsilon_{cc}$) values. a: Scatter plot with line of equality. b: Bland Altman plot.
negative) in the lateral wall, and lowest (least negative) in the inferior wall and septum.

There were no significant differences between pre- and postcontrast peak systolic \( \varepsilon_{cc} \) measurements for either technique, although postcontrast measurements showed greater variability with HARP. One of the factors limiting the clinical use of CMR-based strain analysis is that it requires the additional acquisition of tagged images. However, the finding in this study that measurement of peak systolic \( \varepsilon_{cc} \) is not affected by gadolinium contrast, particularly with SinMod, means that tagged images could be acquired in the (often redundant) period between administering gadolinium contrast and the late-enhancement “acquisition window,” thus not impacting on scan length or patient throughput. This finding also means that tagged images can be acquired to assess strain when unexpected late-enhancement is seen; a not infrequent clinical scenario. The more recent development of a feature tracking-based deformation analysis from SSFP images, which does not require any additional image acquisition, may further facilitate clinical use of strain assessment, although CMR-tagging remains the reference standard at present (27).

Myocardial strain is an attractive marker of myocardial dysfunction given that it declines in the early stages of several cardiovascular disorders, and is noninvasive. However, despite being available for several years, initially echocardiography-based and more recently using CMR, strain has not yet become a routine clinical tool. Reasons for this are multifactorial, including poor reproducibility and time-consuming postprocessing of early techniques, a lack of normal reference ranges, the lack of prospective studies demonstrating improved patient outcome with strain-based therapeutic decision-making and the lack of widespread availability of strain analysis software. Nevertheless, there is a clear need for biomarkers of early myocardial dysfunction given that heart failure, which will affect 1 in 5 people over the age of 40, has a 1-year mortality rate of over 20% (28). This study demonstrates the utility of an alternative method to that of HARP for quantifying strain from tagged CMR images. The availability of another method of quantifying strain, which appears to have generally higher observer agreement, is quicker and is less affected by

<table>
<thead>
<tr>
<th>Table 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agreement Between Harmonic Phase (HARP) and Local Sine-Wave Modeling (SinMod) Analysis Methods for Measurement of Peak Systolic Circumferential Strain (( \varepsilon_{cc} )) According to Ejection Fraction (EF), End-Diastolic Volume (EDV), and Pattern of Myocardial Dysfunction</strong></td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>EF</td>
</tr>
<tr>
<td>EF ( \geq 55% )</td>
</tr>
<tr>
<td>EF ( &lt; 55% )</td>
</tr>
<tr>
<td>Indexed EDV</td>
</tr>
<tr>
<td>EDV ( \geq 90 ) mL/m(^2)</td>
</tr>
<tr>
<td>EDV ( &lt; 90 ) mL/m(^2)</td>
</tr>
<tr>
<td>Dysfunction pattern</td>
</tr>
<tr>
<td>Global</td>
</tr>
<tr>
<td>Regional</td>
</tr>
</tbody>
</table>

Indexed EDV refers to EDV indexed to body surface area.

![Figure 7. Interobserver and intraobserver variability for measurement of global and segmental peak systolic circumferential strain (\( \varepsilon_{cc} \)) using local sine-wave modeling (SinMod) and harmonic phase (HARP) analysis methods. Variability (calculated as \( 1 - r \) where \( r \) is the intraclass correlation coefficient [ICC]) is significantly lower for segmental \( \varepsilon_{cc} \) measurements than for global strain measurements using both techniques. SinMod had significantly lower intraobserver variability than HARP for measurement of global \( \varepsilon_{cc} \). SinMod also had significantly lower inter- and intraobserver variability than HARP for pooled segmental \( \varepsilon_{cc} \) measurements. Ant, anterior segment; AntLat, anterolateral segment; InfLat, inferolateral segment; Inf, inferior segment; InfSep, inferoseptal segment; AntSep, anteroseptal segment; Pooled, pooled segmental analysis. An * denotes a significant difference, assessed using a Wilcoxon rank comparison of the squared differences (*P* < 0.05). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
contrast, may lead to improved access to strain analysis software. However, SinMod requires further evaluation, including assessment of its accuracy in depicting subtle changes in strain with incremental Dobutamine stimulation, assessment of its ability to detect transmural strain gradients and assessment of its accuracy in the other orthogonal directions (17). The study also serves to demonstrate the high observer agreement of HARP for measurement of global εcc in patients with myocardial disease, and that it can be applied postcontrast, factors which may further aid the application of strain assessment.

The main limitation of this study is that no comparison is made to an externally validated gold standard. Reproducibility of strain measurements, requiring 2 separate scans has also not been assessed. Only a single strain direction has been evaluated, although this is in keeping with other studies (7,9,27).

In conclusion, SinMod and HARP-based assessments of global mid-ventricular LV peak-systolic εcc have a high level of agreement across a range of myocardial diseases. Agreement for segmental εcc is substantially lower. The SinMod technique has generally lower observer variability, is quicker and is less affected by contrast, however it requires further evaluation.

ACKNOWLEDGMENTS

C.A.M. was supported by a Doctoral Research Fellowship from the National Institute for Health Research, UK. M.S. was supported by Greater Manchester Comprehensive Local Research Network funding. G.P.M. and C.D.S. received support from the NIHR Leicester Cardiovascular Biomedical Research Unit, and additionally, C.D.S. was funded by the British Heart Foundation.

REFERENCES