

Interobserver Variability in Assessing Segmental Function can be Reduced by Combining Visual Analysis of CMR Cine Sequences with Corresponding Parametric Images of Myocardial Contraction

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ABSTRACT

Objective: To evaluate if color-coded parametric images could help subjective visual analysis and improve interobserver agreement in the evaluation of segmental contraction (SC) in CMR. **Background:** Routine evaluation of SC in CMR remains mostly based on visual analysis of cine loops and subsequent interobserver variability remains a potential drawback. **Materials and methods:** Three short axis cine loops were obtained in 33 subjects (18 myocardial infarction, 15 control), and 528 segments were analyzed. From each cine loop a single static parametric image resuming wall motion information was generated using Factor Analysis of Medical Image Sequences. Three readers (R1, R2, R3) scored left ventricular SC in 4 classes in 2 steps: visual assessment of cine loops alone and by combining cine loops with the corresponding parametric image. Reference segmental scores were obtained by consensus. Global contraction indexes were calculated in each step of the analysis. **Results:** When parametric images were combined with cine loop assessment, interobserver agreement was enhanced for paired readers: R1-R2: $\kappa = 0.66$ (combined analysis) vs. $\kappa = 0.60$ (cine alone); R2-R3: $\kappa = 0.67$ vs. $\kappa = 0.65$; R3-R1: $\kappa = 0.71$ vs. $\kappa = 0.67$ and absolute agreement with consensus was higher for the 3 readers: R1: 91% vs. 85%; R2: 87% vs. 83% and R3: 94% vs. 89%. When considering global wall motion indexes, interobserver agreement was also enhanced: R1 vs. R2: $r = 0.91$ vs. 0.85 ; R2 vs. R3: 0.95 vs. 0.91 ; R3 vs. R1: 0.98 vs. 0.91 . **Conclusion:** Adding a color-coded static parametric image to routine subjective visual assessment of SC reduces interobserver variability.

INTRODUCTION

Accurate evaluation of segmental contractile function remains central to the detection of coronary artery disease (CAD) and to the evaluation of myocardial viability. Furthermore, it has been shown to allow for the estimation of global LV function in CAD (1) and has therefore important diagnostic and prognostic implications (2). Ideally, to allow wide compliance to CAD management guidelines, techniques evaluating segmental contraction (SC) should be minimally invasive, accurate and reproducible. Echocardiography is readily available and image quality has increased but interobserver reproducibility remains far from optimal both at rest and under stress (3, 4).

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Cine CMR allows for the detection of regional contraction abnormalities at rest after myocardial infarction (5) and during dobutamine stress both visually (6) and quantitatively (7, 8). As CMR has the advantage to be a native matricial acquisition allowing to study wall thickening without geometrical assumptions most early studies in CMR relied on wall motion and thickening analysis (9–11). Yet, this approach is impaired by high regional thickening variability and still requires contour tracing thus leaving cine loop reading to be considered the practical reference standard for the evaluation of SC. However, the reproducibility and accuracy of visual assessment of cine loops, owing to the lack of gold standard, had not been extensively documented. Data from recent studies (3, 12, 13) demonstrate that despite superior and constant image quality owing to higher spatial resolution, anatomical coverage and better acquisition standardization than echocardiography (6, 14–17) disappointing interobserver reproducibility remains a drawback, especially in the demanding context of stress examinations (12). Visual assessment of SC necessitates a complex mental integration of parameters such as wall thickness and thickening, endocardial motion, myocardial and cavitory deformation, global movement and temporal parameters leading to a subjective decision making process much influenced by training and experience. Semi quantitative or quantitative methods have been proposed to decrease interpretation bias based on analysis of intramyocardial deformation on tagged images (18–21), endocardial motion tracking (22) or segmental thickening quantification (5, 23). However, since most quantitative post processing methods remain time consuming, SC evaluation remains routinely dependant on visual examination of CMR cine sequences by trained observers.

Although Fourier Analysis has been shown to be a feasible approach in CMR in a pilot study (24) Factor Analysis of Medical Image Sequences (FAMIS) method being a data driven instead of model driven approach has been shown to be superior to Fourier analysis in nuclear medicine (25) and validated in echocardiography (26). FAMIS summarizes ventricular wall motion during the cardiac cycle on a single, immediately generated, tricolor image.

The aim of this study was to evaluate if adding objective parametric images could help subjective visual analysis and improve inter observer agreement in the evaluation of segmental myocardial contraction in CMR.

MATERIAL AND METHODS

Study population

Thirty-three subjects (27 men, 6 women; mean age 54 years $\pm$ 16 [SD]) were included in the study: 18 patients admitted for myocardial infarction and 15 control subjects having no prior cardiovascular history, no cardiovascular risk factors or long-term medication. Informed consent was obtained for all subjects. Subject characteristics are summarized in Table 1.

Table 1. Study population characteristics (n = 33 subjects)

Men	27 (82%)
Women	6 (18%)
Age (years)	54 $\pm$ 16
Myocardial Infarction	18 (55%)
Control	15 (45%)
LVEF* > 60%	17 (52%)
35% < LVEF* < 60%	10 (30%)
LVEF* < 35%	6 (18%)

*LVEF = Left Ventricular Ejection Fraction

CMR Acquisition protocol

Contraction cine loops were obtained using Fast Imaging Employing Steady State Acquisition (FIESTA), a steady state free precession (SSFP) technique, according to a standard protocol on a 1.5-T MRI system (Signa LX, General Electric Medical Systems, Waukesha, Wisconsin, USA) using ECG gating with fiber-optic leads and an 8-element thoracic phased-array surface coil. All MR images were obtained using breath-holding. Cine loops were acquired in short-axis views from the atrio-ventricular rings to the apex using the following parameters: TR: 4.2–4.8 ms, TE: 1.7 ms, flip angle: 45°, view-per-segment: 14–16, cardiac phases: 25–32 after view sharing, slice thickness: 8 mm, imaging matrix: 256 $\times$ 160 pixels, FOV: 32–40 cm.

Image segmentation

Three short axis cine loops, basal, mid-ventricular and apical, were selected. For each level, LV center and anterior attachment of the right ventricular wall to the LV were manually defined in end-diastole by an independent operator. Angular segments were automatically traced according to the recommended model (27) and applied to cine loops and corresponding parametric images to be presented for visual assessment.

Image processing: Factor analysis

The principle of FAMIS to generate a parametric image representing myocardial motion through the cardiac cycle in CMR is summarized in Fig. 1 and detailed in Appendix 1. FAMIS is an automated “data-driven” method which extracts main myocardial motion information (contraction-relaxation curve) and constant component by analyzing the time signal intensity curve variation of each pixel over a cardiac cycle. In particular, normal segments are represented by a band of positive values located along the endocardial wall, as walls with paradoxical motion are represented by a band of negative values. Positive variations are coded in red whereas negative variations are coded in blue to distinguish inward motion from outward motion. Pixels remaining within the cavity or the myocardium through the cycle are coded in green. Finally, the two color maps are superimposed to provide a single tricolor image synthesizing motion information in each myocardial slice.

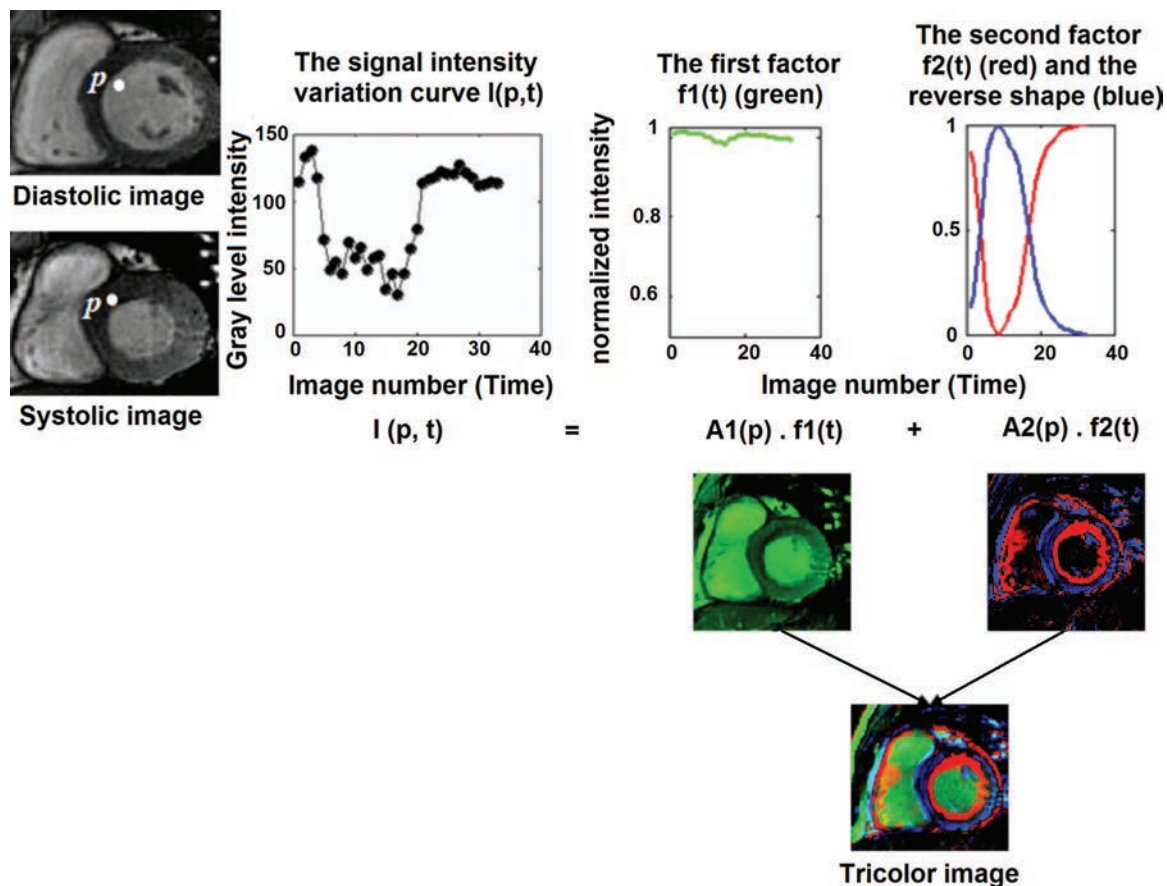


Figure 1. Principle of FAMIS to generate a single parametric image resuming myocardial motion contained in a cine loop. FAMIS analyses for each pixel (p) the time-signal intensity curves $I(p, t)$ which are expressed as the sum of two factors $f_1(t)$ and $f_2(t)$, weighted respectively by coefficients $A_1(p)$ and $A_2(p)$, yielding two parametric images A_1 , and A_2 . The first parametric image A_1 , coded in green, represents only positive and baseline values during the cardiac cycle. The second parametric image A_2 , corresponding to contraction-relaxation curve, $f_2(t)$, represents either positive (red) or negative (blue) values. A tricolor parametric image resuming motion information is obtained by the superimposition of A_1 and A_2 .

General reading rules

Segmental contraction was independently assessed visually by 3 readers (R1, R2, R3) using a 4 class score (normal: 4; hypokinesia: 3; akinesia: 2; dyskinesia: 1) (27, 28). Although all accustomed to CMR contraction interpretation the 3 readers had respectively junior (2 years: R1), senior (4 years: R2) and expert (18 years: R3) experience levels. Presentation of images was anonymous and randomized, and readers were blinded to clinical data.

Native cine loop interpretation was made according to commonly accepted criteria. The interpretation of tricolor parametric images was made according to specific reading rules described in Appendix 2 and Fig. 2. Prior to the interpretation of parametric images, readers were shortly trained (mean time: 2 hours) to recognize different color patterns corresponding to normal and abnormal contraction on a specific separate dataset and shown examples of potential pitfalls: septal contraction, global translation, normal cardiac movements such as the systolic descent of the mitral annulus or motion of papillary muscles.

Image interpretation and data analysis

Image interpretation by the 3 readers was done on anonymized datasets in 4 consecutive steps (Fig. 2):

- 1) reading of native cine loops alone,
- 2) second reading of native cine loops alone to estimate intra observer variability separated by a 2 months delay from the first reading of native cine loops to minimize recall bias and immediately followed by step 3 once recorded,
- 3) combined reading of native cine loops and corresponding parametric images, and
- 4) reference segmental contraction scores were obtained by a consensus reading of the 3 readers.

Image quality both for cine loops and parametric images was rated by the readers for all segments as being suitable or unsuitable for SC diagnosis.

Global contraction indexes were defined as the sum of the segmental contraction scores divided by the number of interpretable segments.

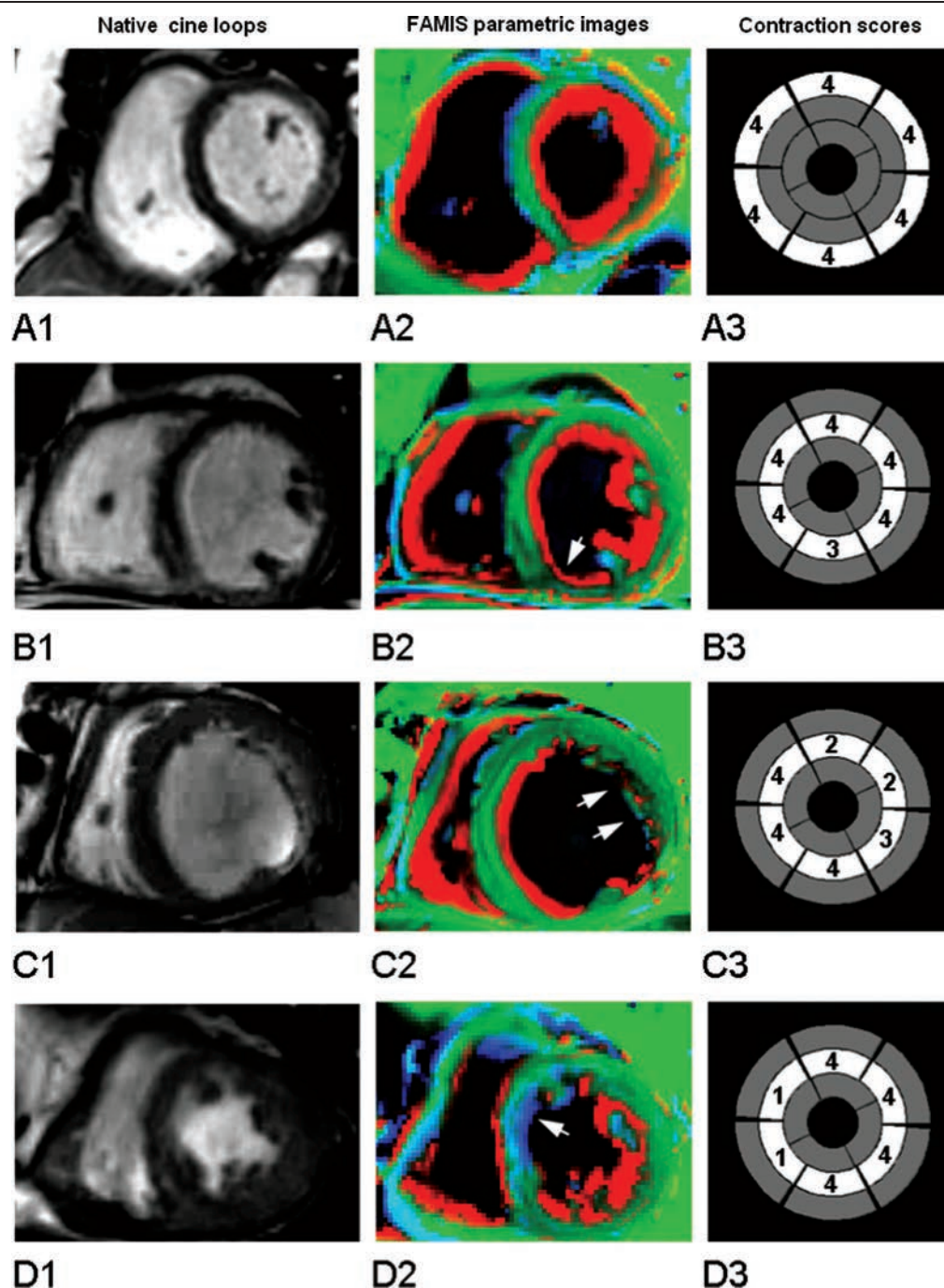


Figure 2. Examples of parametric images illustrating segmental contraction patterns and visual scoring. **Top row (A):** Control subject: basal cine loop (A1) shows normal LV contraction; parametric image (A2) displays a large endocardial red band and corresponding negative epicardial motion coded in blue representing normal systolic myocardial motion and thickening. **Second row (B):** Patient having inferior and inferoseptal myocardial infarct: mid-LV cine loop (B1) shows inferior and inferoseptal marked hypokinesia; parametric image (B2) shows an inferior and inferoseptal thin red endocardial band corresponding to severely decreased motion and thickening in the infarcted area (white arrow). **Third row (C):** Patient having anterior and anterolateral infarction: mid-LV cine loop (C1) shows basal anterolateral and anterior akinesia; parametric image (C2) shows absence of anterolateral endocardial red band with discreet red/green mosaic band and almost entirely green segments (white arrows). The bordering inferolateral segment is only hypokinetic as shown by the presence of a thin red endocardial band. **Bottom row (D):** Patient having transmural anteroseptal infarction: mid-LV cine loop (D1) shows basal anteroseptal thinning and dyskinesia; parametric image (D2) shows a large endocardial blue (negative) band and corresponding red band representing motion of the septum toward the right ventricle (white arrow). The last column shows bull's eye diagrams for each example corresponding to visual contraction scores: 4: normal; 3: hypokinesia, 2: akinesia; 1: dyskinesia.

Statistical analysis

The study of intra and interobserver variability was made using linear weighted Kappa coefficients (29) to take into account the degree of deviation. The degree of agreement was classified as follows: value of κ = strength of agreement: <0.20 = poor; $[0.21-0.40]$ = fair; $[0.41-0.60]$ = moderate; $[0.61-0.80]$ = good; $[0.81-1]$ = very good (30). The agreement between observers and the consensus considered as the reference was evaluated by the absolute agreement defined as the percentage of segments for which the SC score provided by the reader is equal to the consensus. Moreover, the sensibility and specificity for the detection of SC abnormalities were calculated. All values were computed both for the whole database (518 segments, $n = 33$) and for the database restricted to myocardial infarction patients (288 segments, $n = 18$).

Global contraction indexes were compared using linear regression analysis and Bland-Altman analysis was conducted to analyse reader variability between cine reading and combined reading (cine + parametric image).

RESULTS

A total of 528 segments were analyzed. A small percentage of segments were judged not interpretable: 18 of 528 (3.4%) for the first and 12 of 528 (2.3%) for the second cine loop reading. The quality and readability of FAMIS images was good: 19 segments (3.6%) were judged unsuitable for SC diagnosis and 13 (2.5%) segments were judged by consensus unsuitable for SC diagnosis for the combined reading of cine loops and parametric images. Concerning parametric images the proximity of the posterior papillary muscle to the adjacent myocardial wall was the main interpretation pitfall in a small proportion of segments but the combined interpretation of the corresponding cine loop removed all ambiguity. Examples of parametric images are shown on Fig. 2.

Qualitative analysis of segmental contraction: reproducibility study

Intra and interobserver segmental contraction score agreement

As shown on Table 2, intraobserver agreement for cine loop readings is good for R1 ($\kappa = 0.70$) and better for R2 and R3 (re-

Table 3. Segmental contraction: agreement between readers and consensus

	Reader 1	Reader 2	Reader 3
Native analysis: cine loops alone			
Absolute agreement	85% (75%)	83% (81%)	89% (81%)
Sensibility	90% (93%)	98% (98%)	80% (83%)
Specificity	95% (88%)	86% (86%)	99% (99%)
Combined analysis: cine loops + FAMIS*			
Absolute agreement	91% (85%)	87% (86%)	94% (90%)
Sensibility	94% (94%)	97% (97%)	87% (90%)
Specificity	97% (95%)	87% (86%)	99% (99%)

Data are κ values indicating the degree of agreement: κ values concerning all subjects ($n = 33$) are printed in roman characters and κ values restricted to the patients with myocardial infarction ($n = 18$) are printed in italics. *FAMIS = Factor Analysis of Medical Image Sequences.

spectively $\kappa = 0.74$ and $\kappa = 0.78$). When considering only the patients with myocardial infarction ($n = 18$), the intraobserver kappa values are lower for all readers and lowest for the junior observer.

When considering all of the subjects ($n = 33$), agreement between paired readers for cine loop readings alone yield moderate ($\kappa = 0.60$) to good ($\kappa = 0.67$) agreement values. Interobserver agreement is increased for all paired readers when parametric images are combined with cine loops with kappa values ranging from 0.66 to 0.71 as resumed in Table 2.

Again, when considering only the patients with myocardial infarction ($n = 18$), interobserver agreement is increased when combining parametric images with cine loops (Table 2).

Agreement with the reference consensus reading

When considering all of the subjects ($n = 33$), absolute agreement between readers and the consensus for the cine loop reading is R1: 85%, R2: 83%, R3: 89% as shown in Table 3. When parametric images are combined with cine loops absolute agreement is both very good and increased for all readers (R1: 91%; R2: 87%; R3: 94%) compared to the interpretation of cine loops alone. When considering only the patients with myocardial

Table 2. Segmental contraction: intra and interobserver agreement.

	Reader 1	Reader 2	Reader 3
Intra observer agreement			
Native analysis: cine loops (2 readings)	0.70 (0.62)	0.74 (0.73)	0.78 (0.73)
Inter observer agreement			
Native analysis: cine loops	0.60 (0.59)	0.65 (0.64)	0.67 (0.65)
Combined analysis: cine loops + FAMIS*	0.66 (0.64)	0.67 (0.66)	0.71 (0.67)

Data are κ values indicating the degree of agreement: κ values concerning all subjects ($n = 33$) are printed in roman characters and κ values restricted to the patients with myocardial infarction ($n = 18$) are printed in italics. Results are given for the three readers (R1, R2, R3). *FAMIS = Factor Analysis of Medical Image Sequences.

infarction ($n = 18$), absolute agreement is increased when combining parametric images with cine loops with an increase of 10% for R1 (Table 3).

As also summarized in Table 3, the combined reading yields increased and high sensitivity and specificity values for the junior reader (R1), and higher sensitivity for R3 with the same high specificity of 99%. R2 shows a tendency to have a different interpretation of the severity of segmental contraction compared to the consensus reading with a higher sensitivity than the other two readers but a lower specificity. These findings remain true when restricting the data to the myocardial infarction patients.

Global contraction index reproducibility

The regression analysis comparing global contraction indexes between readers shows higher correlation with the combined analysis of cine loops and parametric images compared to cine loops alone with respective correlation coefficients of 0.91 vs. 0.85 (R1); 0.95 vs. 0.91 (R2); and 0.98 vs. 0.91 (R3). Furthermore, the Bland-Altman analysis (Fig. 3) shows a higher reproducibility of the combined reading compared to cine loop reading alone for the 3 readers and illustrates the tendency of R2 to underscore compared to the other 2 readers.

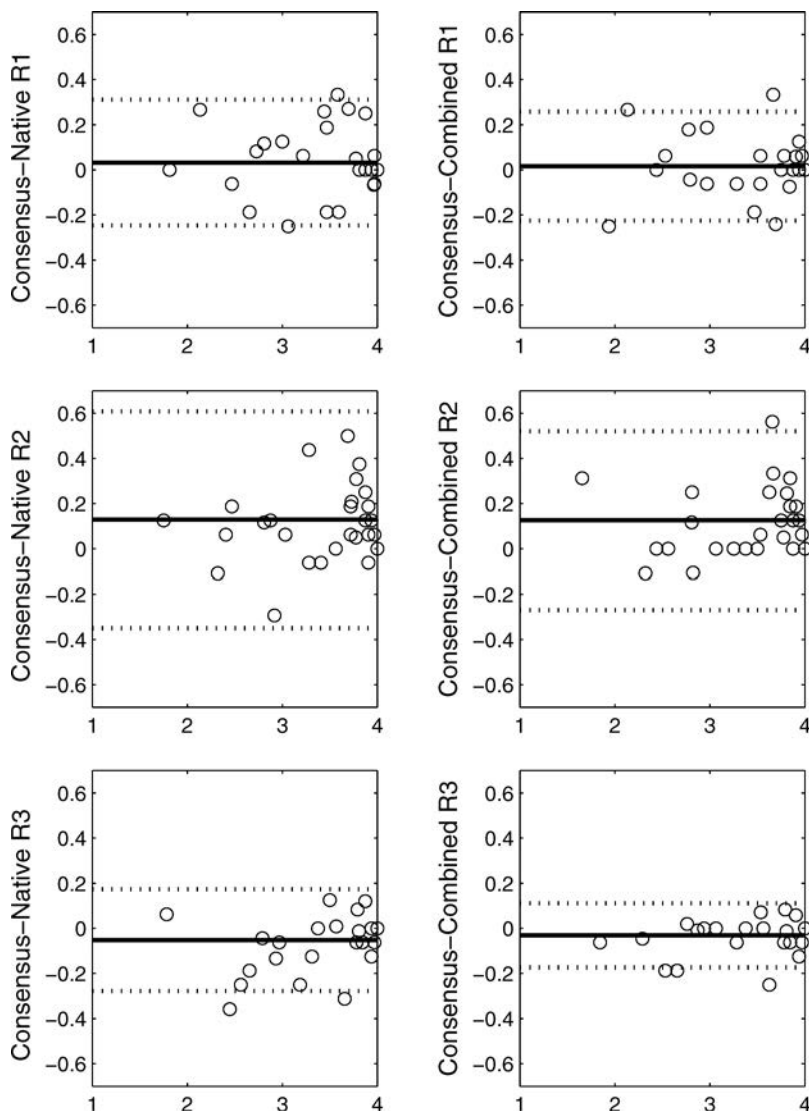


Figure 3. Bland-Altman analysis of reader to consensus variability comparing cine reading with combined reading (cine + parametric image). The plots illustrate for the three readers (R1, R2, R3) a better reproducibility for the combined reading (cine + parametric image) than for cine reading alone. The solid line denotes the average difference and the dotted lines denote ± 2 SDs. The plots in the middle row illustrate the slight systematic bias in classifying segmental contraction by R2 compared to a consensus reading as the average difference, close to 0 for the other readers, is for R2 higher than 0.1 with nevertheless a better reproducibility for the combined reading.

DISCUSSION

The main conclusions from our study are the following: intra and interobserver reproducibility in evaluating SC using visual parameters are good but not optimal using CMR cine loops alone and the combined visual analysis of cine loops and corresponding still frame parametric images reduces interobserver variability and enhances agreement with a reference consensus reading.

Our data suggest that adding parametric images to the routine analysis of cine loops increases interobserver reproducibility and may bolster individual confidence in the subjective analysis of SC.

Considering the intraobserver variability of cine loops interpretation our study showed kappa values between 0.70 and 0.78 rated good (30) but somewhat disappointing. It is noteworthy that kappa values increased with experience as the junior reader had, as expected, the lowest and the expert reader the highest kappa value.

Interobserver agreement for cine loops alone are comparable to those previously reported and can indeed be considered sub optimal considering excellent imaging quality with CMR. In particular, Hoffmann et al. (3) recently reported a low mean unweighted kappa value of 0.43 for the scoring of segmental contraction by cine CMR, which could be partially explained by a substantial overread by an off-site reader and a best value of 0.79. Paetsch et al. (12) reported a mean kappa value of 0.59 among three expert readers in stress cine CMR. The unweighted kappa coefficients in our study, reported here only for comparison purposes, were in the same range with a mean value of 0.54. When considering interobserver agreement, we found higher kappa values for the 3 paired readers when adding parametric images to cine loops with a higher increase in kappa for the junior reader. In the absence of any true gold standard for the evaluation of segmental contraction, the consensus reading was considered as a reference dataset. Our data comparing readers and the consensus shows already good agreement values for cine loop interpretation alone but higher values for all readers were obtained when adding parametric images with an excellent absolute agreement of 94% for the expert reader and the highest increase for the junior reader. When restricting to the patients having myocardial infarction to minimize the impact of the large number of normal segments, we found a comparable gain in agreement, sensitivity and specificity values. The highest increase in absolute agreement of 10% was found for the junior reader (R1). These findings suggest that the addition of parametric images may enhance individual diagnostic confidence.

The comparison of global contraction indexes between readers also showed better correlation when parametric images were added to cine loops despite our relatively limited study population. Simultaneous interpretation of multiple cine loops is difficult and experience dependant. Furthermore, consistently with the literature our study shows that, independently from experience, trained observers may not be equally "calibrated" in terms of final decision with a somewhat different perception of

abnormality and severity. As reported by Hoffmann et al. (3), one of our readers (R2) had a tendency to overrate the severity of segmental contraction by one class when compared to the consensus introducing a slight systematic bias while having good intra and interobserver agreement values. The junior reader (R1) had, as expected, a lower intraobserver reproducibility but nevertheless good agreement with the consensus reading. If reduced variability does not equate to improved accuracy, accuracy studies concerning segmental contraction are, however, difficult to conduct as there is no true gold standard defining normality for an individual. Furthermore, classifying segmental contraction visually remains challenging, especially when deciding between two adjacent classes.

As suggested recently (4), our postulate was that still frame images could be easier to interpret and provide higher interobserver reproducibility and agreement with a reference reading especially if they summarized myocardial motion by displaying an objective parameter. The FAMIS method allows to automatically generate still tricolor parametric images on a basic computer in a few seconds. The resulting parametric image being a mapping of the displacement of the whole myocardium during a cardiac cycle both endocardium and epicardium are depicted thus providing a semi quantitative approach to border movement and indirect illustration of segmental thickening without contour tracing. Consistently with the literature, image quality with SSFP cine was found to be excellent (12). Consequently, the quality of parametric images, dependent on the quality of the native sequence, was satisfactory. Only 2 hours were necessary for each reader to learn the reading rules for the analysis of parametric images. We found that color patterns associated with physiological movements such as papillary muscle displacement, septal thickening toward both the RV and LV, systolic descent of the mitral annulus, all potential pitfalls, could be recognized by the readers. The readers were also able to detect global motion on the parametric images as a thin color band (red-blue pattern) around the structures independent of cardiac motion. The amplitude of these movements was always lower than the proper cardiac wall displacement. Nevertheless, parametric images were always complemented by cine loops in our study to avoid any ambiguity.

Contraction heterogeneity within ischemic myocardium and the passive movements affecting bordering areas contribute to the great segmental thickening variability found in patients with myocardial infarction with border based methods (31–34). The complexity of physiological LV contraction (35) combining radial and longitudinal compression together with torsion partly explains, together with the through plane motion approximation inherent to all tomographic imaging techniques without internal reference markers (36), the wide range of segmental thickening values found in normal segments (31). Furthermore, contouring errors can be responsible for cumulative errors on chordal length measurements and remain a drawback.

The main limitation of this study was that FAMIS is a method that allows precise spatial mapping of myocardial displacement but without quantification. However, contrary to border based

methods, the FAMIS method does not require contour detection or tracing to provide a global parametric map of wall displacement to be visually interpreted. As illustrated on Figs. 1 and 2, all pixels corresponding to moving myocardium are depicted, thus illustrating myocardial thickening and not only endocardial displacement. Our study focused on cine MRI without tagging. Tagged CMR has been shown to allow for the quantification of myocardial strains (18, 37, 38). However, as with segmental thickening quantification techniques, myocardial strains remain variable within a segment ranging from normal to abnormal values and may lead to a potential overlap bias. Averaging values of strain defined as the deformation gradient in larger myocardial segments remains necessary as well as clinical validation. A remaining limit of FAMIS is the lack of temporal imaging. In particular, the detection of ischemic segments with delayed contraction only and almost normal thickening (tardokinesia), although seldom, could be missed. This limit could be overcome by combining amplitude imaging as provided by FAMIS with a temporal imaging method such as color kinesis (39) or PAMM method (40).

Considering the clinical implications of accurate and reproducible SC evaluation interobserver reproducibility of visual CMR cine loop analysis, although considered a reference, remains insufficient. The integration of complex motion and timing information contained in cine loops remains very much dependent on the experience and training of the observer. The standardization of the interpretation of SC remains an issue. As no simple quantification of a few parameters can actually describe accurately SC, we hypothesized that an intermediate approach, complementing routine visual analysis of cine loops with the combined visual analysis of an objective parametric image would enhance interobserver reproducibility and found FAMIS a fast and automatic way to display parametric images resuming SC. Simple reading rules for parametric images are easy to learn and apply by readers of different experience levels and increases individual confidence level for the final decision concerning SC scoring.

FAMIS parametric images combined with conventional CMR cine loops is a feasible approach to increase interobserver reproducibility in evaluating segmental contraction, especially for less experienced readers. In addition, FAMIS is an interesting self-evaluation and teaching tool to help in the understanding and diagnosis of complex SC abnormalities.

ABBREVIATIONS

CAD	coronary artery disease
CMR	cardiac magnetic resonance imaging
FAMIS	factor analysis of medical image sequences
FOV	field of view
LV	left ventricle
LVEF	left ventricular ejection fraction
PAMM	parametric analysis of main motion
SC	segmental contraction
SSFP	steady state free precession

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APPENDIX 1

Factor analysis model for LV function assessment (Figure 1)

Factor Analysis of Medical Image Sequences was developed to synthesize an image sequence into a few parametric images, called factor images and associated time signal intensity curves, called factors (41). It is a two-step data driven analysis, which works with the time signal intensity curves (TSIC) associated to each pixel in the image. The first step is a principal component analysis applied to the TSIC, followed by a selection of the first principal components, to reduce the dimension of the raw data and improve their signal to noise ratio. The second step is an oblique analysis, based on physiological constraints in order to estimate TSIC representative of raw data.

In case of a cine loop corresponding to a single cardiac cycle, two main TSIC shapes are present (26): the first one is a roughly flat curve which corresponds to pixels remaining either inside the cavity or in the myocardium during the whole cardiac cycle; the second one has a “decreasing-increasing” shape; it corresponds to pixels initially inside the cavity, close to the endocardial wall: their signal decreases in systole then increases in diastole because of the overlapping movement of the contracting endocardium and therefore corresponds to a contraction-relaxation curve. Thus a model with two factors $f_1(t)$ and $f_2(t)$ and two factor images $A_1(p)$ and $A_2(p)$ was shown to be appropriate to synthesize the cine loop. Then, the TSIC $I(p, t)$ corresponding to each pixel p can be described as a weighted sum of the two factors :

$$I(p, t) = A_1(p) \cdot f_1(t) + A_2(p) \cdot f_2(t) + e(p, t),$$

$e(p, t)$ being the residual error.

Furthermore, in case of LV motion, simple physiological constraints related to the shape of the factors $f_1(t)$ and $f_2(t)$ and their standardization, which provide a unique non ambiguous solution, have been proposed for echocardiographic data in (26) and were applied here to CMR data. Finally, the two factor images A_1 and A_2 , which can be deduced by least-squares estimation from $I(p,t)$, $f_1(t)$ and $f_2(t)$, can be interpreted as follow: A_1 represents only positive and roughly constant values during the cardiac cycle, it is coded in green; A_2 corresponds to contraction-relaxation curves, represents either positive values, coded in red, or negative values, coded in blue. A tricolor parametric image resuming motion information over the cardiac cycle is obtained by the superimposition of A_1 and A_2 .

The application was easily implemented using the Pixies (Apteryx, Issy-les-Moulineaux, France) developer edition.

APPENDIX 2

Reading rules concerning FAMIS parametric images (Figure 2)

Segmental contraction was considered normal when a large homogenous endocardial red band corresponding to inward displacement was seen with or without a corresponding blue band on the epicardium; hypokinesia was defined as a thin endocardial red band (diminished endocardial motion) bordering a green or red/green mosaic myocardial wall; akinesia was defined as the absence of red endocardial band (absence of endocardial motion), the segment appearing exclusively green or green mosaic; dyskinesia was defined as a thinned segment presenting a thin blue endocardial band and thin red epicardial band (paradoxical movement).