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Impact of image reconstruction on phase analysis of ECG-gated myocardial perfusion SPECT studies

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Abstract

Objectives—Phase analysis (SyncTool) has been developed to assess left-ventricular (LV) dyssynchrony from gated myocardial perfusion single-photon emission computed tomography (GSPECT) studies. Conventionally, GSPECT data are reconstructed using filtered backprojection (FBP). This study is intended to determine the impact of various iterative reconstruction methods on SyncTool.

Methods—Thirty consecutive patients, acquired using a Philips CardioMD system, were enrolled in this study. The GSPECT data were reconstructed using FBP, maximum likelihood expectation maximization (MLEM), MLEM with three-dimensional resolution recovery (Astonish), MLEM with Vantage attenuation correction (AC), and MLEM with Vantage AC and three-dimensional Monte Carlo-based scatter correction (ACSC), respectively. The reconstructed data were then submitted to SyncTool to measure LV dyssynchrony (phase standard deviation and histogram bandwidth). The paired *t*-test was used to compare the LV dyssynchrony indices given by MLEM, Astonish, AC, and ACSC, respectively, with those given by the FBP.

Results—No statistical significance was observed for any comparison between iterative reconstruction methods and the FBP.

Conclusion—Reconstruction methods have insignificant impact on the LV dyssynchrony indices, indicating that the standard FBP reconstruction is sufficient for accurate phase analysis, supporting the widespread clinical use of SyncTool in measuring LV dyssynchrony.

Keywords

gated myocardial perfusion single-photon emission computed tomography; image reconstruction; left-ventricular dyssynchrony; phase analysis

Introduction

Cardiac resynchronization therapy (CRT) is approved for the treatment of patients with end-stage heart failure, depressed left-ventricular (LV) ejection fraction (LVEF) ($< 35\%$) and prolonged QRS complex on the surface ECG (> 120 ms). Improvements from CRT, such as quality of life, functional class, exercise capacity, and LVEF have been demonstrated in multiple studies [1-4]. Notably, two studies have shown survival benefits of CRT [5,6].

Using standard criteria for selecting patients for CRT, approximately 30–40% of patients fail to benefit from CRT [7]. It has been suggested that electrical dyssynchrony as determined by QRS duration may not necessarily represent mechanical dyssynchrony and, therefore, might not represent the best predictor of response to CRT [8-10]. Therefore, cardiac mechanical dyssynchrony has been investigated recently in order to more accurately select patients who would more consistently benefit from CRT. Recent studies have shown that LV mechanical dyssynchrony measured by tissue Doppler imaging (TDI) can predict patient response to CRT [11-13]. However, the Predictors of Response to Cardiac Resynchronization Therapy trial showed that individual TDI measures of mechanical dyssynchrony added little to the ability to predict patient response to CRT. The relatively high intercorelab variability in quantifying the degree of mechanical dyssynchrony was a significant hindrance to the study [14].

Recently, phase analysis (SyncTool, Emory University, Atlanta, Georgia, USA) has been developed for the assessment of LV dyssynchrony from gated single-photon emission computed tomography (GSPECT) myocardial perfusion imaging (MPI) [15]. This technique approximates the variation of LV wall thickness using continuous Fourier harmonic functions so that it has sufficient temporal resolution to analyze LV dyssynchrony [16]. This technique was shown to appropriately discriminate between normal controls and various patient cohorts (left bundle branch block, right bundle branch block, ventricular paced rhythms, and LV dysfunction with LVEF $< 40\%$), who were expected on average to have different degrees of LV dyssynchrony [17]. Moreover, SyncTool showed good correlation with TDI in a study including 75 heart failure patients [18] and good sensitivity and specificity ($> 70\%$) for the prediction of response to CRT in a study including 42 heart failure patients [19].

The earlier studies of phase analysis used the GSPECT images reconstructed by filtered backprojection (FBP) –the conventional, most widely used reconstruction method. Iterative reconstruction methods such as maximum likelihood expectation maximization (MLEM), MLEM with three-dimensional (3D) resolution recovery, and attenuation correction (AC) and scatter correction (SC) are now clinically available. These iterative methods have undergone expensive clinical validations and shown to improve the quality of myocardial perfusion images and diagnostic accuracy [20-29]. However, the iterative methods have not yet been validated for GSPECT studies and their value in improving the accuracy of LV function measurement such as LVEF, and LV systolic and diastolic volumes remain unclear. Phase analysis is a count-based method using the partial volume effect. Simply stated, any myocardial wall that has a linear dimension that is less than twice the spatial resolution of an imaging system will exhibit reduced maximal counts in the direction of that dimension in proportion to change in length [30]. This linear proportion between the change in maximal counts and the change in myocardial wall thickness has been demonstrated in a phantom experiment [31]. Therefore, reconstruction may have larger impact on LV dyssynchrony measurement than LV function measurement, as the former is count-based and the latter mainly depends on myocardial wall edge detection. The purpose of this study is to compare various clinically available iterative reconstruction methods with the FBP in measuring LV dyssynchrony.

Materials and methods

Patients

Thirty consecutive patients, acquired using a Philips CardioMD system (Cleveland, Ohio, USA), were enrolled. This cohort included six patients with cardiomyopathy, 10 patients with coronary artery disease, and 14 patients without definite heart disease, and among them nine patients with hypertension. All of the patients underwent rest sestamibi GSPECT MPI. Four of the 30 enrolled patients did not have stress scan because of their severe heart failure, and therefore 26 patients had stress ^{99m}Tc sestamibi GSPECT MPI (17 had exercise stress and nine had adenosine stress). The stress and rest scans were performed on separate days with 30 mCi of ^{99m}Tc sestamibi injected, respectively. Twenty percent energy windows of approximately 140 and 100 keV were used to acquire the emission and transmission images, respectively. A total of 64 projections (24 s/projection, total acquisition time of 14 min) were obtained over a 180° circular orbit. The GSPECT acquisition acquired 8 frames/cardiac cycle. Data were stored in a 64×64 matrix with 6.4 mm/pixel.

Processing

All GSPECT data were reconstructed using the following five methods with their manufacturer recommended parameters.

1. FBP: Butterworth low-pass filtering with a cut-off frequency of 0.5 Nyquist and an order of 5;
2. MLEM: 30 iterations, starting from a uniform image;
3. MLEM with AC (Vantage Pro, Cleveland, Ohio, USA): 30 iterations for emission reconstruction, starting from a uniform image and 12 iterations for Bayesian transmission reconstruction, starting from a uniform image;
4. MLEM with AC and SC with 3D Monte Carlo-based scatter modeling (available with the Philips Jetstream workstation, Cleveland, Ohio, USA): 30 iterations, starting from a uniform image;
5. MLEM with 3D resolution recovery (Astonish, Cleveland, Ohio, USA): 30 iterations, starting from a uniform image.

All reconstructed data were reoriented to generate gated short-axis images and then submitted to phase analysis. Phase standard deviation and phase histogram bandwidth were automatically calculated as quantitative measures of LV dyssynchrony [15]. Figure 1 shows the processing steps for phase analysis.

Statistical analysis

Paired *t*-tests ($N = 30$ for rest, $N = 26$ for stress) were used to compare the LV dyssynchrony indices given by MLEM, AC, Astonish, and ACSC with those given by the FBP. Paired *t*-tests were also used to compare the LV dyssynchrony indices between the rest and exercise stress studies ($N = 17$) and between the rest and adenosine stress studies ($N = 9$), respectively. A *P* value of less than 0.05 was considered statistically significant.

Results

Phase analysis showed that eight of the 30 patients had severe LV dyssynchrony based on the published normal limits [15]. Both phase standard deviation and histogram bandwidth were greater than 2 standard deviations from the normal mean values. The eight patients with severe LV dyssynchrony included the six patients with cardiomyopathy and two coronary artery disease patients.

The LV dyssynchrony indices given by the FBP and by the iterative reconstruction methods are compared in Fig. 2. None of the comparisons showed statistical significant differences for the stress studies and rest studies. These data showed that phase analysis of GSPECT MPI studies, no matter what reconstruction method was used, produced essentially similar results.

The LV dyssynchrony indices measured by the FBP were compared between the exercise stress studies and rest studies and between the adenosine stress studies and rest studies. Figure 3 shows the results. The LV dyssynchrony indices measured from the exercise stress studies are systematically smaller than those measured from the rest studies in the same patients. The LV dyssynchrony indices measured from the adenosine stress studies are similar to those measured from the rest studies in the same patients. Similar findings were observed from the data reconstructed by the iterative reconstruction methods.

Figure 4 shows a patient example. This patient had nonischemic cardiomyopathy with depressed LVEF ($LVEF < 35\%$). The exercise stress and rest GSPECT MPI data were reconstructed using FBP, MLEM, MLEM with 3D resolution recovery, MLEM with AC, and MLEM with AC and SC, respectively, and then submitted to SyncTool. As shown in this figure, all of the reconstruction methods resulted in essentially similar phase histograms, phase standard deviations, and histogram bandwidths. This example also showed that exercise stress had increased LV synchronicity.

Discussion

The phase analysis has been developed and validated to measure LV mechanical dyssynchrony from GSPECT MPI data. All of its validations used the GSPECT short-axis images reconstructed by FBP – the standard, most widely used reconstruction method for GSPECT MPI data. The FBP takes minimal computation time and does not require additional transmission scans. Iterative reconstruction methods, especially those with AC, resolution recovery, and scatter correction, have shown to improve image quality and diagnostic accuracy for myocardial perfusion assessment [20-29]. However, as shown in this study the benefits from iterative reconstruction methods were insignificant for LV dyssynchrony assessment although the phase analysis is a count-based technique. This study compared the phase analysis of GSPECT MPI data reconstructed using FBP, MLEM, MLEM with AC, MLEM with ACSC, and MLEM with 3D resolution recovery. All of the reconstruction methods produced essentially similar results. We had shown that compared with existing iterative methods, standard FBP reconstruction is as accurate as iterative methods in measuring phase standard deviation and histogram bandwidth extracted from conventional GSPECT MPI data. These findings support the widespread clinical use of phase analysis in measuring LV dyssynchrony.

The iterative reconstruction methods analyzed in this study had a major limitation to LV function assessment – the transmission scans were not gated. The AC and ACSC used attenuation maps averaged over the cardiac cycle, as is the current custom. Therefore, the AC and ACSC applied similar count changes on every frame so that their impact on LV dyssynchrony assessment was insignificant. Radionuclide-based transmission imaging has limited count densities. Thus, even if it was made to acquire gated transmission scans, the accuracy of AC and ACSC could be limited because of low count densities in the transmission images. AC and ACSC based on gated computed tomography scans will be possible to improve LV dyssynchrony assessment and remain to be investigated.

This study also showed a trend that GSPECT data acquired from the exercise stress, but not the adenosine stress, could yield more synchronized phase distribution (smaller phase

standard deviation and narrower phase histogram) from the phase analysis than those acquired from the rest for the same patients. It is not surprising, because adenosine stress does not increase oxygen demand and its hemodynamic effects are less than exercise stress. In addition, the delay time from stress injection to acquisition was shorter for exercise stress than for adenosine stress, so that the exercise stress study was closer to peak stress than the adenosine stress study. As most of the MPI studies are carried out using the same-day protocol and usually only the stress scans are gated, it is important to relate the LV dyssynchrony indices measured from stress scans to those measured from baseline resting scans. However, considering the limited size of the cohort, this relationship cannot be established from this study and requires further investigation.

Conclusion

The phase analysis of GSPECT MPI data, reconstructed by FBP and iterative methods with compensations for physical factors, produced essentially similar results. Standard FBP reconstruction is as accurate as iterative methods in measuring phase standard deviation and histogram bandwidth extracted from conventional GSPECT MPI data. These findings support the widespread clinical use of phase analysis in measuring LV dyssynchrony.

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Fig. 1.

Processing steps for phase analysis. Gated myocardial perfusion single-photon emission computed tomography (GSPECT) myocardial perfusion imaging (MPI) short-axis images served as input. The images underwent three-dimensional (3D) sampling to get regional maximum counts over 600 regions of the left ventricle (LV). The regional maximum counts were proportional to the wall thickness of the region. Regional wall-thickening curves were then constructed and submitted to the Fourier analysis. The phase of the first Fourier harmonic function was used to represent the onset of mechanical contraction. Phase polar map and phase histogram bandwidth were used to quantify LV dyssynchrony. For the patient example shown in this figure, the phase polar map shows a significant phase delay (bright region) at the anterior and apical wall. The location of the phase delay matches well with the perfusion defect shown in the perfusion polar map.

Fig. 2.

Comparisons of the left-ventricular (LV) dyssynchrony indices [phase standard deviation (SD) and histogram bandwidth] given by the iterative reconstruction methods to those given by the filtered backprojection (FBP) of the stress (a) and rest (b) studies. The iterative reconstruction methods compared in this figure include maximum likelihood expectation maximization (MLEM), MLEM with attenuation correction (AC), MLEM with AC and Monte Carlo based scatter correction (ACSC), and MLEM with Astonish resolution recovery (AST). None of the comparisons (paired t-test) show statistical significance, indicating that reconstruction method has insignificant impact on phase analysis.

Fig. 3.

Comparisons of the left-ventricular (LV) dyssynchrony indices [phase standard deviation (SD) and histogram bandwidth, measured by the filtered backprojection (FBP)] between the exercise stress and rest studies and between the adenosine stress and rest studies. The LV dyssynchrony indices measured from the exercise stress studies are systematically smaller than those measured from the rest studies of the same patients. The LV dyssynchrony indices measured from the adenosine stress studies are similar to those measured from the rest studies of the same patients.

Fig. 4.

Patient example. Shown in this figure are phase histograms of exercise stress and rest gated myocardial perfusion single-photon emission computed tomography (GSPECT) myocardial perfusion imaging (MPI) data reconstructed by filtered backprojection (FBP), maximum likelihood expectation maximization (MLEM), MLEM with Astonish three-dimensional resolution recovery (AST), MLEM with attenuation correction (AC), and MLEM with AC and scatter correction (ACSC), respectively. SD, standard deviation.