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High-Resolution MRI of Cardiac Function With Projection Reconstruction and Steady-State Free Precession

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Abstract

The purpose of this study was to investigate the trabecular structure of the endocardial wall of the living human heart, and the effect of that structure on the measurement of myocardial function using MRI. High-resolution MR images ($0.8 \times 0.8 \times 8$ mm voxels) of cardiac function were obtained in five volunteers using a combination of undersampled projection reconstruction (PR) and steady-state free precession (SSFP) contrast in ECG-gated breath-held scans. These images provide movies of cardiac function with new levels of endocardial detail. The trabecular-papillary muscle complex, consisting of a mixture of blood and endocardial structures, is measured to constitute as much as 50% of the myocardial wall in some sectors. Myocardial wall strain measurements derived from tagged MR images show correlation between regions of trabeculae and papillary muscles and regions of high strain, leading to an overestimation of function in the lateral wall.

Keywords

cardiac function; projection reconstruction; radial imaging; trabeculae; True FISP; SSFP; myocardial wall motion; papillary muscles

Visualization of the isolated heart by means of dissection shows that a significant fraction of the myocardial mass is trabecular tissue (1). This is not appreciated in most in vivo cardiac imaging methods which evaluate function. The purpose of this study is to investigate the trabecular structure of the endocardial wall of the living human heart, and the effect of that structure on the measurement of myocardial function, with MRI—specifically using MRI to measure muscle shortening. Anterior-lateral myocardial muscle shortening has been measured to be greater than septal shortening using myocardial tissue tagging (2,3). Is this an artifact caused by the presence of trabecular tissue on the free wall?

In order to investigate the importance of fine endocardial structures of the heart wall, very high-resolution 2D segmented ECG-gated images of the heart were acquired by combining two techniques: projection reconstruction (PR) acquisition (6-8), and steady state with free precession (SSFP) contrast (4,5). A PR acquisition acquires data with radial trajectories, and produces greater resolution per unit time compared to Cartesian imaging, by use of azimuthal undersampling (9). In this study an undersampling factor (N_x/N_r) of 1.5 was employed, using a 400 readout resolution and 256 projections. This undersampling is minimal compared to other investigations (6,7,9-11), because fast imaging was not the purpose. The goal was to obtain the highest possible resolution, limited by the constraints of a 32-s breath-hold, signal-to-noise

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ratio (SNR) limitations, and temporal resolution of about 40 ms, to investigate the impact of small structures on cardiac imaging. A 32-s breath-hold is not feasible for most patients. However, these high-resolution movies of the heart reveal new features of the left ventricular (LV) wall, which influence measures such as wall thickening and wall strain. The resolution achieved was $0.8 \times 0.8 \times 8$ mm, i.e., a 2D voxel that is roughly five times smaller than that of standard images (12,13).

The reported spatial resolution of MR images of cardiac function varies somewhat, dependent on the acquisition method, but is usually lower than that presented in this study. For non-breath-hold, non-ECG-gated (real-time) assessments of cardiac function (14-18), in-plane resolution ranges from 1.4×2.1 to 2.2×4.4 mm. Two recent studies of the performance of segmented ECG-gated SSFP imaging of the heart employed in-plane resolution of about 1.4×2.2 mm (12,13). Recent reports using the PR-SSFP technique employed 1.2×1.2 to 2.3×2.3 mm resolution (6,7).

For cardiac imaging methods like tagging, delayed hyperenhancement imaging, and first-pass perfusion imaging, in-plane resolution is similarly moderate. For first pass perfusion imaging resolutions are typically 3×3 mm (19,20), reflecting acquisition of multiple slices in a single heartbeat. Imaging of myocardial infarction with delayed hyperenhancement uses in-plane image resolutions of 1.2×1.2 mm (21). Myocardial tagging studies have been published with resolutions of 2.2×1.1 mm (22), 1.4×3.2 mm (23), and 2.1×1.2 mm (24).

The resolution obtained in most cardiac studies, as described above, provides images of diagnostic value. However, the present high-resolution study using PR-SSFP reveals the fine structures on the endocardial surface. These structures, if not resolved, may bias measurements of cardiac function. These structures consist of a complex of trabeculae and papillary muscles (the trabecular-papillary muscle complex). The zone in which this mixture of blood, trabeculae, and papillary muscles resides is here called the trabecular zone. The types of MR images that will be influenced by the presence of these endocardial features include tagging studies, wall-motion imaging, stress studies, and contrast enhancement studies such as perfusion imaging and delayed hyperenhancement imaging. This work examines in depth only the influence of the trabeculae and papillary muscle complex on myocardial wall tagging studies, and by inference, nontagged function studies.

This study investigates the hypothesis that the improved spatial resolution provided by the PR-SSFP technique can delineate the trabeculae and papillary muscles through the cardiac cycle. In some endocardial regions, tagging studies often treat the trabecular-papillary muscle complex as myocardial tissue, showing visually and quantitatively a strain pattern that is due primarily to the collapse of loosely connected trabeculae and papillary muscles, and only secondarily to regional contraction. Nontagged wall motion studies of function may show wall thickening that is due not only to contraction but also to compression and folding of the trabecular-papillary muscle complex. MRI exams to observe pharmacologically induced ischemia may also be influenced by this effect when low-resolution tagging or function exams are used (25). The present high-resolution images may explain possible errors in various estimators of myocardial function using lower-resolution techniques.

METHODS

This study presents the results from five normal volunteers. All human subjects provided informed consent in accordance with the Internal Review Board of our institution.

Data Acquisition

The sequence was implemented on a GE 1.5T CV/i scanner, equipped with 40 mT/m maximum gradient strengths, and 150 T/m/s slew rates. Figure 1 shows a sketch of the 2D pulse sequence diagram for PR-SSFP. Segmented prospectively-gated acquisitions (eight views per segment) in a 32-heartbeat breath-hold provided a temporal resolution of 30–40 ms. The excitation pulse was a sinc or truncated sinc pulse, and the slice-select gradient pre- and rephasers were played simultaneously with the readout-gradient pre- and rephasers. In accordance with the pulse sequence requirements for creating SSFP (4), each TR is zeroth-order gradient-moment nulled, and 180° phase cycling is applied to the excitation pulse (Fig. 1a). For some studies, first-order moment nulling over each TR was also used for the *x*, *y*, and *z* gradients (Fig. 1b). First-moment nulling was necessary in basal short-axis slices to reduce flow artifacts. Typical scan parameters were: TR/TE (zeroth-moment nulled) = 3.8 ms/1.1 ms, TR/TE (zeroth- and first-moment nulled) = 4.8/2.1, flip angle = 50°–60°, field of view (FOV) = 32 cm, slice thickness = 8 mm, 400 readout points, 256 projections spanning 180°, ± 125 kHz bandwidth, and cardiac phased-array coil. The in-plane spatial resolution was 0.8 × 0.8 mm. Multiple breath-holds were used to acquire multiple short-axis slices. The raw data was reconstructed offline on a Silicon Graphics workstation (SGI, Mountain View, CA), using a regridding algorithm (26) and 2D Fourier transform.

The acquisition of tagged myocardial images was performed in the same slice using fast gradient echo imaging. At the time of each ECG-trigger, spatial modulation of magnetization (SPAMM) (27) presaturation pulses were applied, consisting of seven RF pulses with a 180° composite flip angle. Grid tags were oriented at 45° to the readout direction and spaced 7 pixels apart. Typical scan parameters were: TR/TE = 5.6 ms/1.4 ms; flip angle = ~12°; FOV = 32 cm; slice thickness = 8 mm; readout resolution = 256, 128, or 256 phase-encodings; ±32 kHz bandwidth; and cardiac phased-array coil. Segmented prospectively ECG-gated acquisitions (eight views per segment) in a 16- or 32-heartbeat breath-hold provided a temporal resolution of about 44 ms. Nontagged images were also obtained, using identical acquisition parameters except for a flip angle of 15°.

Quantification Methods

With the high-resolution PR-SSFP images it was possible to measure the extent of the trabecular zone (a mixture of blood, trabeculae, and papillary muscles), which we call the trabecular fraction. Three contours were manually drawn in the LV, as shown in Fig. 2a: the endocardial border, including the trabecular-papillary muscle complex (dotted line); the endocardial border, excluding the complex (dashed line); and the “epicardial” border (solid line). The trabecular fraction for each sector was defined as the ratio of the area of trabecular-papillary muscle zone (A_{trab} , dashed minus dotted line) to the total myocardial area (A_{allmyo} ,

solid minus dotted line):
$$F = \frac{A_{trab}}{A_{allmyo}}$$
 The trabecular fraction was measured in three slices for five volunteers. The data from the five volunteers was pooled to provide the trabecular fraction as a function of the myocardial sector for basal, mid-level, and apical slices. The trabecular fraction of the myocardium was quantified for 16 arcs around the myocardium at end-diastole. These 16 arcs consisted of finer divisions of the six standard echocardiographic sectors shown in Fig. 2b. The labeling convention of Fig. 2b was used for displaying the results.

The ratio of blood residing in the trabecular zone at end-diastole to the total blood area in the LV at end-diastole was also measured. A region of interest (ROI) was used to define the area of the blood pool in the nontrabecular zone ($A_{bp-nontrab}$) (area inside dotted line in Fig. 2a), and thresholding was used to define the area of blood in the trabecular zone ($A_{bp-trab}$). The fraction of blood residing in the trabecular zone was evaluated as:

$$F = \frac{A_{bp-trab}}{A_{bp-trab} + A_{bp-nontrab}}.$$

Myocardial wall strain measurements were performed to investigate the strain in regions of observed trabeculae and papillary muscles. A 2D strain analysis was performed using FindTags, a tag detection and strain computation software program (28), on tagged images to calculate circumferential shortening (circumferential strain). For contouring of the tagged images, no reference was made to the PR-SSFP images that showed trabecular structures. Average circumferential shortening at end-systole was obtained from epicardial and endocardial layers in six sectors (defined as in Fig. 2b) around the myocardium. This data was pooled for all volunteers, and the average strain at end-systole was plotted. The high-resolution PR-SSFP images of the same slice and time frame were used to identify endocardial sectors in which the trabecular-papillary muscle zone contained coherent tag lines (which subsequently were used in strain calculations). The strains from these regions were separated from nontrabecular strains, and the resulting mean strains were compared.

RESULTS

Figure 3 shows a representative time series of images of a single short-axis slice, throughout the ejection phase of the cardiac cycle (end-diastole to end-systole), using high-resolution PR-SSFP. These images are best appreciated as a movie, which is available on the internet (29). The LV wall contains the trabeculae and papillary muscles everywhere except over a 60° arc centered on the septum. At end-systole, the trabecular and papillary muscle structure is less visible due to compression and folding of the trabeculae and papillary muscles. In some regions at end-systole the compressed trabeculae appear as a segment of continuous myocardial tissue.

Blood and myocardium SNR and contrast-to-noise ratio (CNR) were measured for the volunteers, each in three short-axis slices, using high-resolution PR-SSFP imaging with scan parameters as described in the Methods section. SNR was quantified using magnitude images as the signal in a large ROI in the myocardium and LV, divided by the standard deviation (SD) of the signal in air space. CNR was measured as the difference in signal between blood and myocardium, divided by the noise. The average blood SNR was 20 ± 8 , average myocardial SNR was 7.3 ± 3 , and CNR was 12 ± 6 . Some images were acquired with full echoes, and others with fractional echoes (asymmetric frequency-encoding), which resulted in a bimodal distribution of SNR values.

Figure 4 shows three short-axis slices at end-diastole from a volunteer. The basal slices have less trabeculation, the papillary muscle structures are clearly disconnected from the wall, and more flow artifact is observed in these slices in a cine loop. The apical slices have greater trabeculation, and the papillary muscles are less distinguishable from trabeculation. There are regions of apparent “marsh,” which appear as blood-myocardium mixtures.

Figure 5 compares frames at end-diastole and end-systole from (a and b) a high-resolution ($0.8 \times 0.8 \times 8$ mm) SSFP movie, and (c and d) a conventional ($1.2 \times 1.2 \times 8$ mm) cine movie. The comparisons are matched in slice position and temporal position in the cardiac cycle. When comparing the end-diastolic images from PR-SSFP (Fig. 5a) and conventional cine (Fig. 5c), it is observed that much of the detail of the trabecular tissue is not resolved in the conventional cine image. In the conventional cine image at end-systole (Fig. 5d), the regions of very fine trabecular and papillary muscle structure have disappeared, and now appear uniformly dark, like myocardium. The papillary muscles are recognizable in all four images. In the end-systolic PR-SSFP image, some detail remains to partially identify the trabecular tissue (Fig. 5b); however, the actual demarcation of the endocardium is difficult.

Fraction of Myocardium That Consists of Trabeculation and Blood

The fraction of the apparent wall, in a short-axis slice, that is trabeculae and papillary muscles mixed with blood was quantified and is plotted against sectors in Fig. 6. This fraction is defined in the Methods section and Fig. 2a. Figure 6 shows the results of quantifying the ratio of the trabecular zone area to the entire wall area for five volunteers, each providing three slices. The fraction is plotted for three short-axis levels: basal, mid-level, and apical. As much as 50% of the myocardial region in some sectors consists of a mixture of blood, trabeculae, and papillary muscle.

The ratio of LV blood residing in the trabecular zone to all LV blood in a slice was measured on the PR-SSFP images at diastole to be $10\% \pm 7\%$ in area.

Myocardial Wall Tagging

To investigate the influence of trabecular and papillary muscle structures on tagging strain measurements, tagged and high-resolution PR-SSFP images were obtained for the same slice. Figure 7 compares a high-resolution image (Fig. 7a) with the corresponding tagged image (b) and circumferential shortening map (c) at end-systole. Arrows in Fig. 7a show regions of trabeculae and papillary muscles. The tagged image (Fig. 7b) shows that these regions correspond to regions with highly displaced tag lines. The strain map (Fig. 7c) confirms this quantitatively. Such comparisons between images of tagged myocardium, strain maps, and high-resolution PR-SSFP images were used to investigate the possibility that the observed high strains on the endocardial border are caused by the trabecular-papillary muscle complex. The PR-SSFP images show complex trabecular structures on the posterior lateral and anterior lateral free wall. Large tissue displacements on the endocardium are observed in the tagged images, and were found to be correlated with the trabecular and papillary muscle structures.

Figure 8 shows circumferential shortening for five volunteers and a total of 11 slices. The mean strains for all volunteers at end-systole for two myocardial layers (endocardial and epicardial) and six sectors are plotted. The trends toward higher strains on the endocardium vs. the epicardium, and higher strains on the posterior-lateral, anterior-lateral, inferior, and anterior wall vs. the septal wall agree with previously reported studies (2,3).

In Fig. 9, the end-systolic circumferential shortening from *endocardial* sectors in the 11 tagged slices that appear to be tagged trabecular zones are plotted separately from nontrabecular zones, using the high-resolution PR-SSFP images for guidance, as described in Methods section and Fig. 2a. Sectors for which the high-resolution images show trabecular-papillary muscle complexes were categorized as trabecular zones. These consisted largely of all sectors except the inferior and anterior septum (see Fig. 2). Greater strains were measured in the trabecular zones. The mean circumferential shortening was -0.200 in the trabecular zone, and -0.174 in the nontrabecular zone. The difference between these strains was 0.026% , or 14% of average strain. The difference is statistically significant using an unpaired Student's *t*-test ($P < 0.01$), when treating the strains in the six myocardial sectors as independent measures. Figure 9 demonstrates that highly trabeculated areas of the endocardium are also areas of higher circumferential strain at end-systole.

DISCUSSION

The nature of the trabecular and papillary muscle structures on the endocardial surface of the heart is well appreciated anatomically (1), but its influence on diagnostic cardiac images has not been assessed. The combination of imaging with SSFP contrast and increased resolution provides a new level of visualizing the trabecular-papillary muscle complex. Others have hypothesized that errors in MR wall motion measurements may be due to trabecular structures

(30); however, this study provides data to directly observe the influence of endocardial structures in MR cardiac function.

The fraction of the LV wall area, in a short-axis slice, that consists of a mixture of blood, papillary muscle, and trabeculae is as much as 50% in some sectors of the myocardium (see Fig. 6). Figure 5 shows that in conventional cine images, depending on the size of the feature, trabeculation appears either dark (like myocardium) or retains its trabecular shape. The endocardial border is not a sharp demarcation between blood and myocardium, but is a trabecular zone with a complex border. The important clinical measurement of LV wall thickening used for assessing states of ischemia in cardiac MRI and echocardiography relies on accurate detection of the endocardial surface, and in practice papillary muscles are excluded. The present investigation suggests that the real inner myocardial border is not easily observed, especially in end-systole (see Fig. 3).

Other investigators (2,3) have measured transmural strain gradients and reported increased strain on the endocardium compared to the epicardium, as was found in the present study. These investigators (2,3) also reported increased strain measurements on the anterior-lateral wall (the free wall) compared to the septum, with higher strains of about 20%. The current study shows similar increases in endocardial strain on the anterior and lateral wall (Fig. 8). Furthermore, these high strains are in sectors with trabecular-papillary muscle complexes.

In tagged imaging, and images from related methods (25,31), the contours that separate the myocardium from the blood pool are identified mainly by the presence of tag lines: coherent tag lines indicate myocardial boundaries. There is very little contrast between nontagged myocardium and blood pool, as observed in Fig. 7. Therefore, slow-flowing ventricular blood, trabeculae, and papillary muscles are sometimes included in strain measurements. In this way, high strains are sometimes measured on the endocardium. In addition, poor visualization of tags may result, not from the standard problems of low SNR, or low spatial or temporal resolution, but because the tagged tissue is trabeculae, papillary muscle, or stagnant blood, rather than heart wall. Contouring of tagged images should avoid incoherent tags, and exclude as much as 50% of the apparent wall thickness in the anterior, lateral, and inferior walls.

Studies have shown that calculations of *global* measures such as LV mass, end-diastolic and end-systolic volume, and ejection fraction (17,18) can be as accurately performed with low-resolution, real-time acquisitions as with ECG-gated, breath-held, higher-resolution imaging. However, a recent study (16) reports that *regional* measures of wall thickening and wall motion using real-time imaging are less accurate compared to measurements from segmented ECG-gated acquisitions, especially in the lateral and anterior walls, with less wall thickening measured by real-time imaging compared to ECG-gated imaging. The greater trabecular zone on the lateral and anterior walls may explain some of the differences, if the higher-resolution images allow the exclusion of these regions in diastole.

This study has implications for the current interest in endocardial injections of therapeutic agents, e.g., angiogenic therapies or alcohol ablations, for the purpose of treatment (32,33). The complex trabecular structure might influence catheter manipulations for therapeutic endocardial injection or ablation, either interfering with an injection or aiding in anchoring the injection. Injections into the septal wall rather than the free wall may provide different challenges. The results of this study are also relevant to noncontact measurements of endocardial electrical activity (34). The vital question is, what is the endocardial surface?

CONCLUSIONS

High-resolution PR-SSFP reveals fine trabeculae and papillary muscles of the beating human heart. This is due to the excellent contrast of SSFP, and the high resolution achievable with

PR. These structures have implications for MRI of the heart. Over an arc of 120° around the LV wall (excluding the septum) there is actually a border zone containing myocardial trabeculae, papillary muscles, and blood. If these trabecular zones are mistaken due to low-resolution imaging, this will lead to a 100% overestimation of the end-diastolic wall thickness in some regions. Myocardial strain measurements of the LV that report higher strain values on the free wall than on the septum are shown to be influenced by the structures on the endocardium, due to tagging of the trabeculae, papillary muscles, and slow-flowing blood. Contouring of the endocardium for the purposes of strain measurements on tagged images should be performed to omit disconnected tag lines, and only the outer 50% of the apparent thickness of the anterior and lateral walls should be used.

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FIG. 1.

A sketch of the SSFP projection reconstruction pulse sequence, with (a) zeroth-moment gradient nulling, and (b) first-moment gradient nulling. The projection at 45° is shown.

FIG. 2.

a: An epicardial contour and two endocardial contours for the high-resolution image are shown. One endocardial contour includes all myocardium (dotted line), and the other excludes the trabecular zone (dashed) of short-axis slices. **b:** Six myocardial sectors, assigned according to echocardiographic convention, were used to report results in this work.

FIG. 3.

A time series of short-axis images of the heart, from end-diastole to end-systole (2D segmented ECG-gated PR-SSFP, $400 \text{ Nr} \times 256 \text{ Np}$, $\text{FOV} = 32 \text{ cm}$, $\pm 125 \text{ kHz BW}$, $\text{TR}/\theta = 4.5 \text{ ms}/50^\circ$, eight views per segment). Spatial resolution is $0.8 \times 0.8 \times 8 \text{ mm}$, with 40-ms temporal resolution. Note the many fine structures of the endocardium.

FIG. 4.

A stack of short-axis slices, from apex (left) to base (right), shown at end-diastole. The trabecular and papillary muscle structures vary throughout the heart.

FIG. 5.
a and **b**: High-resolution PR-SSFP images of the heart at end-diastole and end-systole ($0.8 \times 0.8 \times 8$ mm). **c** and **d**: Conventional gradient echo images ($1.2 \times 1.2 \times 8$ mm) at the same spatial and temporal positions as **a** and **b**, respectively. In the conventional images, discrimination of the endocardial border is challenging at end-diastole and becomes impossible at end-systole.

FIG. 6.

The fraction of the wall thickness that comprises the trabecular and papillary muscle structures is plotted against the myocardial sector (as defined in Fig. 2b), averaged for five volunteers, for apical, mid-level, and basal slices, at end-diastole.

FIG. 7.

(a) High-resolution PR-SSFP image, (b) the tagged image, and (c) the circumferential shortening map, all at end-systole. The images show that (a) regions of papillary and trabeculae are also regions of (b) visually and (c) quantitatively high strains. The circumferential shortening map is scaled from -0.10 (white) to -0.25 (black).

FIG. 8.

Averaged circumferential shortening measured for the 11 analyzed slices from five volunteers, separated into six myocardial sectors (see Fig. 2b) and two layers. The strain is greatest in the anterior and lateral walls. There are higher strains on the endocardium.

FIG. 9.

The endocardial circumferential strains in the trabecular zones vs. strains in nontrabecular zones are shown, as measured by tagged myocardial wall imaging. The strains are highest in trabecular regions. The SDs of the two distributions are also plotted.