

## Altered right ventricular papillary muscle position and orientation in patients with a dilated left ventricle

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**Objective:** To investigate the impact of left ventricular dilatation on right ventricular papillary muscle displacement.

**Methods:** Thirteen patients underwent high-resolution cardiac magnetic resonance imaging at Emory University Hospital: Seven patients with congestive heart failure and a dilated left ventricle composed the dilated left ventricular group, and 6 normal subjects were used as a control. A total of 120 cardiac magnetic resonance imaging slices were acquired in a short-axis view at end diastole for each subject. Cardiac magnetic resonance imaging slices were used to identify the papillary muscle tip position in 3-dimensional coordinates for the septal, posterior, and anterior papillary muscles. The centroid of the papillary muscle coordinates was used as the reference point for comparison between subjects. The relative orientation between the right ventricular papillary muscles was evaluated and compared between the dilated left ventricular group and normal subjects.

**Results:** Dilatation of the left ventricle resulted in a significant ( $P = .05$ ) displacement of the septal right ventricular papillary muscle toward the centroid: normal group,  $0.0285 \pm 0.036$  mm/mm versus dilated left ventricular group,  $0.1437 \pm 0.026$  mm/mm. More specifically, the septal papillary muscle significantly ( $P = .03$ ) moved away from the septal wall (normal group:  $0.61 \pm 0.09$  mm/mm, dilated left ventricular group:  $0.379 \pm 0.037$  mm/mm). Specific locations of all 3 right ventricular papillary muscles were reported for normal subjects and patients with a dilated left ventricle.

**Conclusions:** Patients with a dilated left ventricle have significantly increased displacement of the septal right ventricular papillary muscle away from the septum when compared with normal controls. This demonstrates pathophysiologic contribution of the left ventricle to specific papillary muscle alterations within the right ventricle. (J Thorac Cardiovasc Surg 2011;141:744-9)

Left-sided heart disease is traditionally thought to affect the right side of the heart through pulmonary hypertension<sup>1,2</sup> and increased afterload on the right ventricle (RV). Left ventricle (LV) dilatation and dysfunction, even in the absence of pulmonary hypertension, can have a detrimental impact on the RV and may be a potential mechanism for high occurrence of tricuspid regurgitation (TR) in patients with mitral regurgitation. In this study, it is hypothesized that pulmonary hypertension geometric changes on the left side may also directly affect the right side because the RV and LV are connected through the interventricular

septum.<sup>3</sup> The volume in which the LV and RV can fill is restricted by the pericardial sack; thus, a dilated LV may enlarge not only into the pericardial space but also into the RV because it is a lower pressure chamber. Changes in RV geometry induced from LV geometric changes may contribute to secondary TR through papillary muscle (PM) displacement, improper muscle contraction, or other complications.

Changes in RV geometry may lead to alterations in the positions of the PMs of the tricuspid valve (TV) because they are directly connected to the ventricle. Jouan and colleagues<sup>4</sup> and Hiro and colleagues<sup>5</sup> investigated the RV PM position in sheep over the cardiac cycle, but they did not report how these positions may change in a diseased state. Studies have implicated RV dilatation as a cause of anterior PM displacement.<sup>6,7</sup> The speculated mechanism for pathologic PM displacement is that as the free wall of the RV dilates, the anterior PM, located on the free wall of the ventricle and attached to the valve leaflets through chordae tendineae, moves outwardly, thus tethering the TV leaflets.<sup>8</sup> In addition to the proposed motion of the anterior PM due to RV dilatation, it is of interest to determine whether the PMs on the septal wall, the posterior and septal PMs, are displaced as the result of LV dilatation. Although it is probable that the septal and posterior PMs are affected by LV dilatation through the interventricular septal motion, it has yet to be demonstrated in

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### Abbreviations and Acronyms

ARP	= annulus reference plane
LV	= left ventricle
MRI	= magnetic resonance imaging
PM	= papillary muscle
RV	= right ventricle
TR	= tricuspid regurgitation
TV	= tricuspid valve

human subjects. The specifics of which PMs are displaced with specific causes, the direction of displacement, and how much they are displaced remain unknown.

If in fact there is an effect on the PMs in the RV as the result of LV dilatation, this may further support the belief that the dynamics on the left side of the heart affect the right side of the heart. We hypothesize that geometric changes in the LV, as a result of LV dilatation, may also alter RV geometry and displace the PMs located on the septal wall.

This study identifies and compares the position of RV PMs in normal subjects and patients with LV dilation to quantitatively establish the RV PM positions and the influence of LV dilation on RV PM displacement. Magnetic resonance imaging (MRI) was the imaging modality chosen for this study because it has the potential to image cardiac structures in high resolution with no radiation dosage.

## MATERIALS AND METHODS

### Patient Selection

A total of 13 subjects were scanned as part of a high-resolution geometric protocol at Emory University Hospital Midtown, Atlanta, Georgia. Of these, 7 were patients with congestive heart failure (dilated LV group) with the following implications: mild ( $n = 2$ ) to severe ( $n = 5$ ) mitral valve regurgitation, a dilated LV (LV end-diastolic volume  $234.7 \pm 70.8$  mL), mean age of  $65 \pm 14$  years, New York Heart Association class 2 ( $n = 2$ ), 3 ( $n = 4$ ), 4 ( $n = 1$ ), pulmonary regurgitation ( $n = 3$ ), pulmonary hypertension mild ( $n = 3$ ) to moderate ( $n = 3$ ), normal systolic function ( $n = 6$ ), and mild TR ( $n = 5$ ). The remaining 6 were normal subjects used as controls for the study (normal group), with no known heart conditions and a mean age of  $25 \pm 2.5$  years ( $n = 5$ ). The study was approved by the Emory University Institutional Review Board for human subjects, patient privacy was protected according to Health Insurance Portability and Accountability regulations, and all patient identifiers were removed from data used in this study. Informed consent was obtained from all participants in the study.

### Image Acquisition

All scans were acquired on a Philips Intera CV 1.5 T (Andover, Mass) system using a cardiac coil. High-resolution, electrocardiogram, and navigator echo-gated "whole heart" gradient echo sequence was used in the short-axis orientation spanning both the RV and LV during end diastole.<sup>9</sup> Pixel size ranged from 0.53 to 0.70 mm, slice thickness ranged from 1.5 to 2.0 mm, and echo time ranged from 1.3 to 2.1 ms. Approximately 120 slices were acquired at end diastole, as confirmed with cine images, to cover the entire LV and RV.

### Data Processing

XnView 1.92 (Pierre-Emmanuel Gougele, France) was used for visualization and post-processing. References in the x, y, and z direction were identified

to compare the PMs in 3-dimensional space. An annulus reference slice was identified to calculate the z distance relative to the annulus reference plane (ARP). The annulus plane was selected as a reference plane so the relative proximity and change could be related to the annulus plane. The ARP was identified as the slice in which the right coronary artery and aortic leaflets were visible. The diameter of the ascending aorta was measured and recorded in the ARP. PM tip position was manually identified in the various images by identifying the regions of low intensity (the PM) among regions of high intensity (blood) in the RV (Figure 1). The first slice in which the PM was visible was recorded to obtain the z distance with respect to the ARP. The x and y coordinates of the center of the PM tip were recorded to give the full 3-dimensional position.

Three-dimensional coordinates were recorded for all 3 PMs: septal, posterior, and anterior in all subjects. All images were registered to the MRI coordinate system for purposes of position and orientation.<sup>10</sup>

The centroid of the 3 PM coordinates was calculated for the 3 PMs for each patient and used as a reference point. All distances were normalized by ascending aortic diameter to minimize patient variability. X, y, and z distances from the centroid (Figure 2, A) were calculated for each PM and the distance from each PM to the centroid (Figure 2, C). In addition, the triangle formed by the 3 PMs was used to investigate the relative position of the PMs. The distance of each triangle side length (Figure 2, B) and area of the triangle formed by the 3 PMs (Figure 2, D) was reported.

PMs were classified into groups on the basis of their location; (i) anterior: located on the free wall; (ii) septal: located on the anterior portion of the septum; and (iii) posterior: located on the posterior portion of the septum.

### Statistical Methods

An Anderson Darling test was used to test for normality. A 2-sample Student *t* test was performed to determine statistically significant differences between normal patients and patients with heart disease. Values are expressed as mean  $\pm$  standard error. A post hoc power analysis was conducted on groups in which a significant difference was noted to confirm appropriate power ( $\geq 0.7$ ).

## RESULTS

### Normal Group

All measurements for normal PM position can be found in Table 1. It is notable that the sides of the triangle formed by the PMs were of similar length. The septal PM was the furthest from the centroid with a normalized distance of  $1.07 \pm 0.08$  mm/mm. The anterior PM was the most apical and furthest from the ARP of the 3 PMs ( $0.20 \pm 0.04$  mm/mm), with the septal PM the closest to the ARP ( $0.85 \pm 0.07$  mm/mm). A 3-dimensional depiction of normal PMs and their position in the heart can be seen in Figure 3.

### Dilated Left Ventricular Group

All measurements for diseased PM position are shown in Table 1. The same relative position and orientation of all 3 PMs was noted in both groups. The septal PM was furthest from the centroid ( $0.76 \pm 0.11$  mm/mm). The anterior PM was furthest away from the ARP ( $0.15 \pm 0.03$  mm/mm), and the septal PM was the closest ( $0.74 \pm 0.05$  mm/mm).

### Differences

Significant differences between normal patients and patients with heart disease were only detectable with the septal PM. The differences were observed in the y distance

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