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QUANTIFICATION OF BIVENTRICULAR MYOCARDIAL STRAIN FROM MAGNETIC RESONANCE IMAGES OF PULMONARY HYPERTENSIVE PATIENTS USING HYPERELASTIC WARPING

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INTRODUCTION

Pulmonary hypertension (PH) is a disease resulting from restricted flow in the pulmonary arterial circulation. This results in an increase in pulmonary vascular resistance. Left untreated, the disease leads to right ventricular (RV) failure, which is the most common cause of death in PH patients. The quantification of RV function is important for clinical management of PH patients, with clinical studies showing that the RV function is a major determinant of the functional capacity and prognosis in PH patients. Recent studies have demonstrated that the RV strain is associated with the RV function, and is a potentially useful prognostic marker in PH patients. Compared to quantifying strain in the left ventricle (LV), which can be approximated by a truncated ellipsoid, the *in vivo* quantitative assessment of the strain in the RV is challenging because of its complex geometry and thin wall. Here, we describe the application of a hyperelastic warping technique for quantifying RV strain in PH patients using regular CINE-MR images, which has the potential to overcome these challenges.

METHODS

In hyperelastic warping, a finite element (FE) representation of the biventricular unit in the template image (T) was constructed and then deformed into alignment with the corresponding object target image (S) during the registration process (Fig. 1a). The forces responsible for the registration deformation were derived from the differences in image intensity between the template image and the target images at different time points in a cardiac cycle. The deformation map is denoted by $\varphi(\mathbf{X}) = \mathbf{x} = \mathbf{X} + \mathbf{u}(\mathbf{X})$, where \mathbf{x} are the current (deformed) coordinates corresponding to \mathbf{X} , and $\mathbf{u}(\mathbf{X})$ is the displacement field. The deformation gradient is given as

$$\mathbf{F}(\mathbf{X}) = \frac{\partial \varphi(\mathbf{X})}{\partial \mathbf{X}}. \quad (1)$$

The local change in volume is directly related to \mathbf{F} through the Jacobian ($J = \det \mathbf{F}$) and the right Cauchy-Green deformation tensor is defined as $\mathbf{C} = \mathbf{F}^T \mathbf{F}$.

Hyperelastic warping can be posed as the minimization of an energy functional E that consists of two terms, this can be defined with respect to the current configuration as:

$$E = \int_{\beta} W(\mathbf{X}, \mathbf{C}) \frac{dv}{J} - \int_{\beta} U(T(\mathbf{X}), S(\varphi)) \frac{dv}{J}, \quad (2)$$

Here, W is the hyperelastic strain energy density function that provides regularization and/or some type of constraint on the deformation map, while U is an image energy density functional that depends on the image data in the template and target images and takes the form:

$$U(\mathbf{X}, \varphi) = \frac{\lambda}{2} (T(\mathbf{X}) - S(\varphi))^2, \quad (3)$$

where λ is a penalty parameter that enforces the alignment of the template model with target image.

In Eq. (2), the first variation of the first term yields the standard weak form of the momentum equations for nonlinear solid mechanics, the first variation of the functional U with respect to $\varphi(\mathbf{X})$ in direction $\boldsymbol{\eta}$ produces the image-based force term:

$$DU(\mathbf{X}, \varphi) \cdot \boldsymbol{\eta} = -\lambda [(T(\mathbf{X}) - S(\varphi)) \frac{\partial S(\varphi)}{\partial \varphi} \cdot \boldsymbol{\eta}]. \quad (4)$$

This term drives the deformation of the template based on the pointwise difference in the image intensities and the gradient of the target intensity evaluated at material points associated with the template [1]. A Neo-Hookean potential with unit stiffness was used for W and the penalty parameter λ was adjusted until the deformation field converges.

The circumferential direction was assigned using Laplace-Dirichlet Rule-Based (LDRB) algorithm (Fig. 1b), which ensures that the circumferential orientation varies smoothly and continuously throughout the entire myocardium [2]. The biventricular unit was divided into 3 material regions, namely, the left ventricular free wall (LVFW), right ventricular free wall (RVFW) and septum (Fig. 1c). The average circumferential strain was computed for each region.

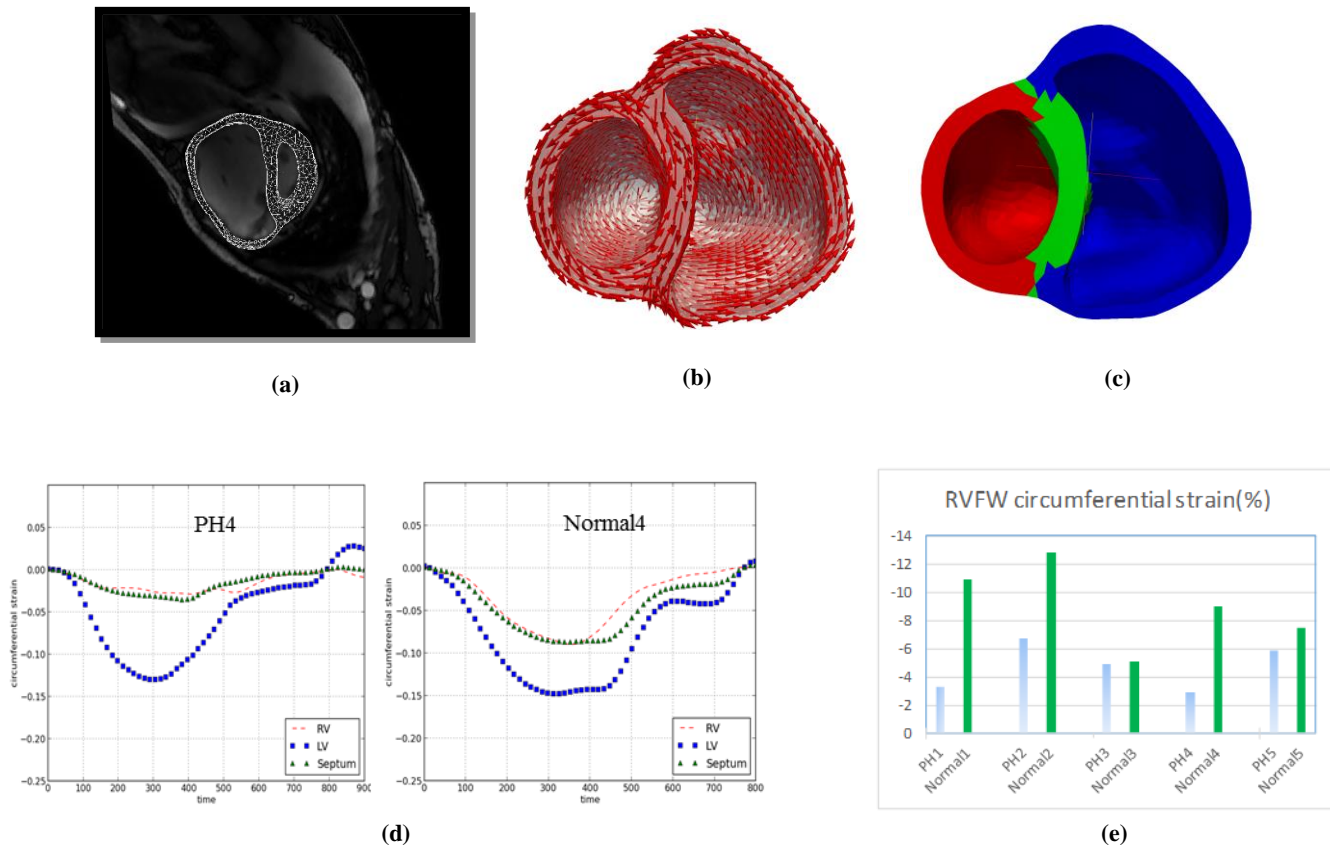


FIGURE 1. (a): segmentation of the biventricular unit in the template image (b): circumferential myocardial fiber orientation (c): 3 material regions (red: LVFW, green: Septum and blue: RVFW) (d): comparison of RVFW, septum and LVFW global circumferential strains between PH4 and Normal4 in one cardiac cycle (e): RVFW global circumferential strains for all patients and healthy controls

RESULTS

The study population consisted of 5 patients with PH, who were diagnosed by right heart catheterization. The control group consisted of 5 healthy adults matched for age and sex. The majority of patients were female with an average age of 50 ± 13 years, average peak RV systolic pressure (62.4 ± 9.0 mmHg), and the average RV end-systolic volume (128 ± 59 mL). Global systolic circumferential strains of RVFW, LVFW and septum were quantified for the patients and controls (Fig. 1d and Fig. 1e). The results showed that all patients had a significant depressed peak RVFW circumferential strain as compared to controls ($-4.7\% \pm 1.6\%$ (PH) vs $9.1\% \pm 3.0\%$ (Normal), $P=0.021$). However, the LVFW and septum peak systolic circumferential strain predictions of patients were not statistically different from those of healthy controls (LVFW: $14\% \pm 4.3\%$ (PH) vs $14.4\% \pm 2.5\%$ (Normal), $P=0.9$; septum: $5.3\% \pm 2.9\%$ (PH) vs $7.2\% \pm 2.0\%$ (Normal), $P=0.275$).

DISCUSSION

In our present study, we used a deformable image registration technique known as hyperelastic warping to quantify the global circumferential strain of the biventricular unit in patients suffering from PH. Our results showed that the PH patients had significantly reduced RV peak systolic circumferential strains as compared with healthy controls. These results are consistent with previous studies, in which strain-encoded MR imaging was adopted to analyze RV peak regional longitudinal and circumferential strain in PH patients. In their study, there were significant reductions of the

peak longitudinal strains at the mid-ventricular and apical levels and the peak circumferential strain at the basal level, which is also qualitatively consistent with our findings

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