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Influence of left-ventricular shape on passive filling properties and end-diastolic fiber stress and strain

H.F. Choi *, J. D'hooge, F.E. Rademakers, P. Claus

Division Cardiovascular Imaging and Dynamics, Department of Cardiovascular Diseases, Katholieke Universiteit Leuven, University Hospitals - Campus Gasthuisberg, Herestraat 49 - Bus 7003, B-3000 Leuven, Belgium

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ABSTRACT

Passive filling is a major determinant for the pump performance of the left ventricle and is determined by the filling pressure and the ventricular compliance. In the quantification of the passive mechanical behaviour of the left ventricle and its compliance, focus has been mainly on fiber orientation and constitutive parameters. Although it has been shown that the left-ventricular shape plays an important role in cardiac (patho-)physiology, the dependency on left-ventricular shape has never been studied in detail. Therefore, we have quantified the influence of left-ventricular shape on the overall compliance and the intramyocardial distribution of passive fiber stress and strain during the passive filling period. Hereto, fiber stress and strain were calculated in a finite element analysis of passive inflation of left ventricles with different shapes, ranging from an elongated ellipsoid to a sphere, but keeping the initial cavity volume constant. For each shape, the wall volume was varied to obtain ventricles with different wall thickness. The passive myocardium was described by an incompressible hyperelastic material law with transverse isotropic symmetry along the muscle fiber directions. A realistic transmural distribution in fiber orientation was assumed. We found that compliance was not altered substantially, but the transmural distribution of both passive fiber stress and strain was highly dependent on regional wall curvature and thickness. A low curvature wall was characterized by a maximum in the transmural fiber stress and strain in the mid-wall region, while a steep subendocardial transmural gradient was present in a high curvature wall. The transmural fiber stress and strain gradients in a low and high curvature wall were, respectively, flattened and steepened by an increase in wall thickness.

1. Introduction

The passive filling capacity of the left ventricle (LV) is an important factor in the performance of the heart. The passive mechanical behaviour, i.e. the compliance, of the left ventricle is a determinant of this capacity. The compliance depends on the microscopic structure of the muscle wall, i.e. the myocardium, which is composed of myocytes, connective tissue and vasculature. Experiments have shown that the myocytes are organized in a complex helical fiber network (Anderson et al., 2009), indicating a mechanical behaviour that is locally anisotropic. The mechanics of the myocytes are described by the regional fiber stress and strain, but a robust experimental quantification remains a challenge. Current intramyocardial methods are invasive and give only information about isotropic pressures (Westerhof et al., 2006), while imaging methods still lack the resolution to obtain accurate intramural strain distributions. These limitations necessitate computational modeling to obtain regional fiber stress and strain values.

Several modeling studies have been performed with this aim (e.g. Bovendeerd et al., 1992; Rijcken et al., 1997; Vetter and McCulloch, 2000; Vendelin et al., 2002). However, the focus of these studies has been mainly on tissue elasticity or fiber orientations, assuming a certain shape of the left ventricle based on gross anatomical measurements. Only limited attention has been paid to the relation between LV shape and regional mechanics. However, in several patho-physiological conditions such as ischemia, changes in mechanical loading of the left ventricle are often accompanied by a change in LV shape through a process called remodelling (Opie et al., 2006), in which the LV tends to become more spherical and/or the wall thickness increases. It can be expected that LV shape and wall thickness will influence regional mechanics directly. To test this hypothesis, fiber stress and strain distributions at the end of the passive filling phase, i.e. end diastole (ED), were compared for different LV shapes and wall thicknesses by means of finite element (FE) modeling.

* Corresponding author.
E-mail address: honfai.choi@uz.kuleuven.be (H.F. Choi).

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2. Methods

2.1. Left-ventricular mesh

The shape of the left ventricle was modeled as a truncated thick-walled ellipsoid. The geometry of an ellipsoid is most conveniently described using curvilinear prolate spheroidal coordinates. The transformations between prolate spheroidal (λ, μ, θ) and Cartesian (x, y, z) coordinates are given by

$$x = f\sinh(\lambda)\sin(\mu)\cos(\theta),$$

$$y = f\sinh(\lambda)\sin(\mu)\sin(\theta),$$

$$z = f\cosh(\lambda)\cos(\mu), \quad (1)$$

where f is the focal length. As shown in Fig. 1(a), the λ-coordinate varies along radial directions perpendicular to confocal ellipsoidal surfaces, while the μ- and θ-coordinates give the longitudinal and circumferential position on these surfaces, respectively. Using this coordinate system, the dimensions of the left ventricle can be varied to obtain shapes with a different degree of sphericity. The initial cavity volume was kept at a constant value of 85 ml to obtain an ED volume of around 100 ml (see Results), which was assumed to be a representative value for the adult human LV based on the recommendations in Lang et al. (2005). The opening at the truncated basal side, which represented the mitral valve annulus, was given a constant diameter of 3 cm, which was assumed to be representative for the adult human LV based on Otto and Bonow (2008).

LV walls were constructed in a two-step process. First the geometry of the endocardial (inner) border aligning the cavity was defined, followed by the construction of the epicardial (outer) border. The normal vectors on the endocardial border were calculated and taken to be the transmural directions (see Fig. 1(b)). The epicardial surface of the LV wall was constructed by moving outward along these transmural directions.

2.2. Fiber orientation and constitutive behaviour

To model the helical pattern of the fiber orientation, a mathematical template as defined by Guccione et al. (1991) was used in which the helical angle varied linearly along the transmural directions from 75° to −45° at the endocardial and epicardial border, respectively (see Fig. 1(c)). The large deformations of the LV myocardium need to be described with the nonlinear theory of finite deformation (Holzapfel, 2000). It was assumed that the left ventricle was in static equilibrium in ED without body forces or couple stresses present, such that Cauchy's equilibrium equation can be applied:

$$\nabla \cdot \underline{\sigma} = 0, \quad (2)$$

where $\underline{\sigma}$ is the symmetric Cauchy stress tensor and ∇ is the nabla-operator. As in most studies, the passive LV myocardium in ED was modeled as an incompressible hyperelastic material with transverse isotropic symmetry aligned with the local fiber direction. For a hyperelastic material, the symmetric second Piola–Kirchhoff stress tensor $\underline{\mathbf{S}}$ is calculated as the derivative of a strain energy function Φ with respect to the Green–Lagrange strain tensor $\underline{\mathbf{E}}$:

$$\underline{\mathbf{S}} = \frac{\partial \Phi(\underline{\mathbf{E}})}{\partial \underline{\mathbf{E}}}. \quad (3)$$

The Cauchy stress tensor is related to the second Piola–Kirchhoff stress tensor $\underline{\mathbf{S}}$ by

$$\underline{\sigma} = J^{-1}\underline{\mathbf{F}} \cdot \underline{\mathbf{S}} \cdot \underline{\mathbf{F}}^{T}, \quad (4)$$

where $\underline{\mathbf{F}}$ is the deformation gradient tensor and J its determinant. The strain energy function Φ is a sum of an isochoric term Φ_{iso}, which determines the incompressible elastic response, and a volumetric term Φ_{vol} that gives the strain energy resulting from changes in volume. To obtain incompressibility, J must be equal to one. This was imposed via a Lagrange multiplier p in Φ_{vol}:

$$\Phi = \Phi_{iso} + \Phi_{vol} = \Phi_{iso} + p(J\text{-}1). \quad (5)$$

The Lagrange multiplier p will enter the stress equations as a hydrostatic pressure. For Φ_{iso}, the function as proposed by Okamoto et al. (2000)

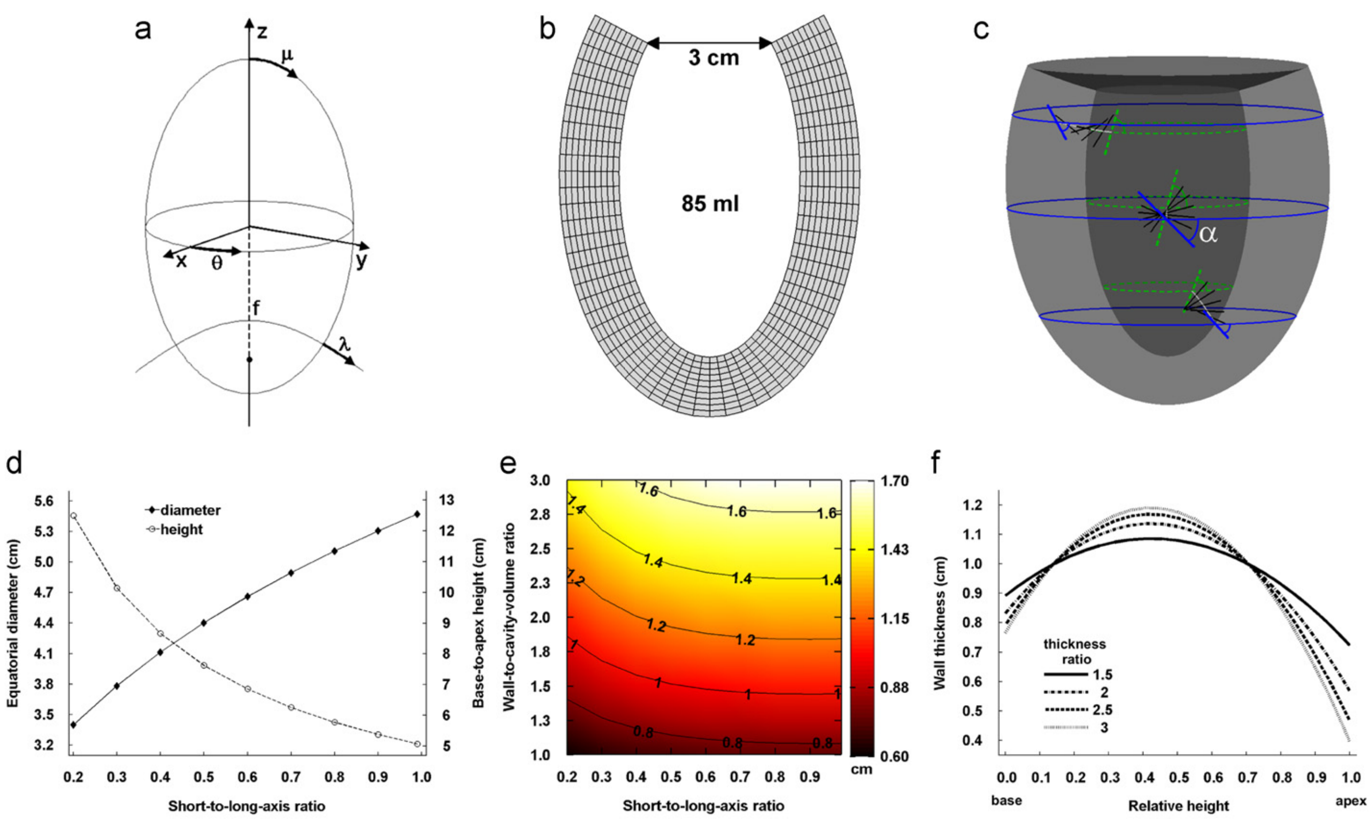

Fig. 1. Dimensions and geometry of the different LV shapes. In (a), the prolate spheroidal coordinate system is illustrated. The longitudinal-transmural cross-section of a FE mesh example of a LV wall with uniform thickness is shown in (b). In (c), the linear varying transmural distribution of the fiber helix angle (α) is illustrated at different longitudinal positions. The equatorial diameter and base-to-apex height of the LV cavities with different short-to-long-axis ratios are shown in (d). The thickness of the uniformly thick LV walls constructed from the LV cavities with different wall-to-cavity-volume ratios are plotted in (e). The variation of the wall thickness in function of the relative height as defined for the LV walls with different equatorial-to-apical-thickness ratios but constant short-to-long-axis ratio (= 0.5) and wall-to-cavity-volume-ratio (= 1.5) are shown in (f).