Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Passive diastolic modelling of human ventricles: Effects of base movement and geometrical heterogeneity

Arnab Palit [a,c,*], Pasquale Franciosa [a], Sunil K. Bhudia [b], Theodoros N. Arvanitis [c], Glen A. Turley [a], Mark A. Williams [a]

[a] WMG, The University of Warwick, Coventry, UK
[b] University Hospitals Coventry and Warwickshire, Coventry, UK
[c] Institute of Digital Healthcare, WMG, The University of Warwick, Coventry, UK

ARTICLE INFO

Article history:
Accepted 19 December 2016

Keywords:
Ventricular diastolic mechanics
Finite element
Patient-specific modelling
Ventricular geometry
Fibre structure

ABSTRACT

Left-ventricular (LV) remodelling, associated with diastolic heart failure, is driven by an increase in myocardial stress. Therefore, normalisation of LV wall stress is the cornerstone of many therapeutic treatments. However, information regarding such regional stress–strain for human LV is still limited. Thus, the objectives of our study were to determine local diastolic stress–strain field in healthy LVs, and consequently, to identify the regional variations amongst them due to geometric heterogeneity. Effects of LV base movement on diastolic model predictions, which were ignored in the literature, were further explored. Personalised finite-element modelling of five normal human bi-ventricles was carried out using subject-specific myocardium properties. Model prediction was validated individually through comparison with end-diastolic volume and a new shape-volume based measurement of LV cavity, extracted from magnetic resonance imaging. Results indicated that incorporation of LV base movement improved the model predictions (shape-volume relevancy of LV cavity), and therefore, it should be considered in future studies. The LV endocardium always experienced higher fibre stress compared to the epicardium for all five subjects. The LV wall near base experienced higher stress compared to equatorial and apical locations. The lateral LV wall underwent greater stress distribution (fibre and sheet stress) compared to other three regions. In addition, normal ranges of different stress–strain components in different regions of LV wall were reported for five healthy ventricles. This information could be used as targets for future computational studies to optimise diastolic heart failure treatments or design new therapeutic interventions/devices.

1. Introduction

Epidemiological studies reported that more than half of the patients diagnosed with heart failure (HF) have left-ventricular (LV) diastolic dysfunction with normal systolic pump function (Wang and Nagueh, 2009). LV remodelling process, associated with diastolic heart failure (HF), was identified to be driven by an increase in LV wall stress (Lee et al., 2014, Wall et al., 2006). The LV remodelling is, therefore, increasingly recognized as a potential target for therapeutic interventions, which include the use of hydrogel injection (Lee et al., 2013a), anisotropic reinforcement (Fomovsky et al., 2012), cardiac support and resistance devices (Lee et al., 2014, Wenk et al., 2013a). The main objective of these surgical interventions was to normalise the LV wall stress at end diastole (ED). Finite element (FE) modelling, in combination with new cardiac imaging modalities and advanced simulation tools, can be used to analyse the diastolic mechanics of healthy heart and identify the normal ranges of stress–strain distribution in LV wall. Such information will provide a greater insight of the physiology and pathophysiology of HF patients, and thereby, predict their response to medical and surgical interventions.

The majority of diastolic FE modelling in existing literature was based on either animal heart or idealised geometry of single LV (Guccione et al., 1995, Costa et al., 1996, Usyk et al., 2000, Vetter and McCulloch, 2000) (Table 1). With the advancement in imaging modalities over the years, subject-specific single LV geometry was used for FE modelling (Wang et al., 2013, Wang et al., 2009, Genet

* Correspondence to: WMG, University of Warwick, Coventry CV4 7AL, UK. Fax: +44 24 7652 4307.
E-mail addresses: arnab.palit@warwick.ac.uk, arnabpalit@gmail.com (A. Palit), P.Franciosa@warwick.ac.uk (P. Franciosa), S.Bhudia@warwick.ac.uk (S.K. Bhudia), T.Arvanitis@warwick.ac.uk (T.N. Arvanitis), Glen.Turley@warwick.ac.uk (G.A. Turley), M.A.Williams.1@warwick.ac.uk (M.A. Williams).

http://dx.doi.org/10.1016/j.jbiomech.2016.12.023
0021-9290/

Table 1
Previous work on passive diastolic modelling of LV with the key attributes considered in the study.

	Single LV		Bi-ventricle (BV)		Effect of base movement
	Animal myocardium passive properties	Human myocardium passive properties	Animal myocardium passive properties	Human myocardium passive properties	
Animal ventricle /Idealised geometry	Humphrey and Yin (1989) Guccione et al. (1995) Costa et al. (1996) Vetter and McCulloch (2000) Usyk et al. (2000) Wang et al. (2009)	-	Stevens et al. (2003)	-	-
Transversely isotropic	Humphrey and Yin (1989) Guccione et al. (1995) Costa et al. (1996) Vetter and McCulloch (2000) Wang et al. (2009)	Genet et al. (2014)	-	-	-
Human ventricle	Wang et al. (2013)	Genet et al. (2014)	Palit et al. (2015)		
Orthotropic	Usyk et al. (2000) Wang et al. (2013)	-	Stevens et al. (2003) Palit et al. (2015) Göktepe et al. (2011)	Research in this paper	
Effect of global Geometric Heterogeneity	-	Genet et al. (2014)	-		

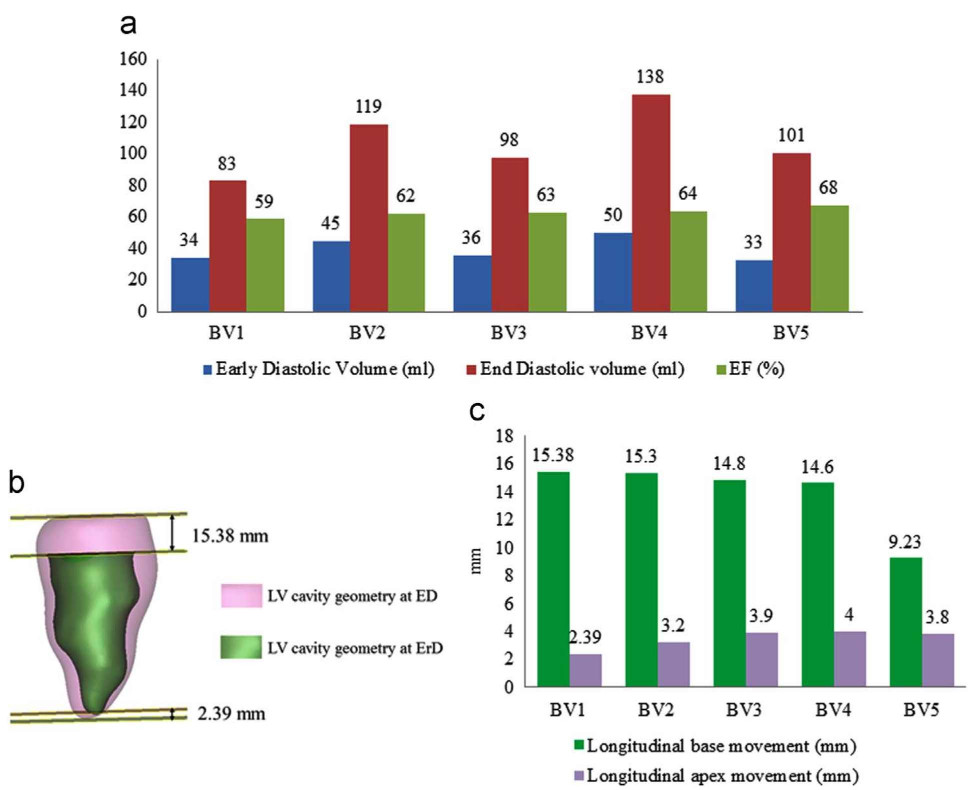

Fig. 1. Subject-specific values. (a) Early Diastolic Volume (ErDV), End Diastolic Volume (EDV) and Ejection Fraction (EF) extracted from CMRI of five normal ventricles (BV1 to BV5); (b) Measurement procedure of longitudinal base and apex movement; (c) Longitudinal movement of base and apex measured for five ventricles (BV1 to BV5).

et al., 2014). Recent study by Palit et al. (2015b) showed that the right-ventricle (RV) deformation has a significant effect on LV wall stress distribution and should be considered during ventricular modelling. Furthermore, in majority of the computational models, Fung-type transversely isotropic constitutive law was used (Guccione et al., 1995, Costa et al., 1996, Vetter and McCulloch, 2000, Wang et al., 2009, Genet et al., 2014) (Table 1). In contrast, simple shear test of pig and human myocardium (Dokos et al., 2002, Sommer et al., 2015b, Gultekin et al., 2016) clearly exhibited orthotropic viscoelastic behaviour. Modified Fung-type (Usyk et al., 2000, Costa et al., 2001) and pole-zero law (Stevens et al., 2003) were used in diastolic modelling to incorporate material orthotropy. However, the material parameters in these orthotropic models were merely used as weighting factors, rather than any physical significance (Göktepe et al., 2011). Recently, Holzapfel and Ogden (2009) developed a constitutive law that considered the