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Research Paper

The cardiac torsion as a sensitive index of heart pathology: A model study

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ABSTRACT

The torsional behaviour of the heart (*i.e.* the mutual rotation of the cardiac base and apex) was proved to be sensitive to alterations of some cardiovascular parameters, *i.e.* preload, afterload and contractility. Moreover, pathologies which affect the fibers architecture and cardiac geometry were proved to alter the cardiac torsion pattern. For these reasons, cardiac torsion represents a sensitive index of ventricular performance. The aim of this work is to provide further insight into physiological and pathological alterations of the cardiac torsion by means of computational analyses, combining a structural model of the two ventricles with simple lumped parameter models of both the systemic and the pulmonary circulations. Starting from diagnostic images, a 3D anatomy based geometry of the two ventricles was reconstructed. The myocytes orientation in the ventricles was assigned according to literature data and the myocardium was modelled as an anisotropic hyperelastic material. Both the active and the passive phases of the cardiac cycle were modelled, and different clinical conditions were simulated. The results in terms of alterations of the cardiac torsion in the presence of pathologies are in agreement with experimental literature data. The use of a computational approach allowed the investigation of the stresses and strains in the ventricular wall as well as of the global hemodynamic parameters in the presence of the considered pathologies. Furthermore, the model outcomes highlight how for specific pathological conditions, an altered torsional pattern of the ventricles can be present, encouraging the use of the ventricular torsion in the clinical practice.

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1. Introduction

The cardiac torsion *i.e.* the mutual rotation of the cardiac base and apex, is conventionally defined as the difference between the cardiac apical and basal cross-sections rotation. A counter-clockwise rotation when viewed from the apex is conventionally assumed as positive. During initial isovolumic contraction, the apex and the base both rotate in a counter-clockwise direction (Lorenz et al., 2000); during the systole the base changes direction and starts to rotate in a clockwise direction, while the apex continues to rotate counterclockwise, causing the torsional peak. This peak is then followed by a rapid untwisting of the ventricle during the isovolumic relaxation: the potential elastic energy stored in the collagen matrix and cytoskeletal proteins (titin) is released (recoil), causing the rapid untwisting (Rademakers et al., 1994; Notomi et al., 2006) and contributing to an active suction of blood from the atria. The cardiac torsion is due to the peculiar architecture of the heart. Several studies highlighted the presence of obliquely oriented muscle fibres whose orientation varies from a right-handed helix at the subendocardium to a left-handed helix at the subepicardium (Torrent-Guasp et al., 2001a,b, 2004, 2005). This spiral organization seems to be fundamental in determining both the cardiac systolic and diastolic function (Arts et al., 1979). The torsional behaviour of the heart was proved to be sensitive to the alteration of some cardiovascular parameters, *i.e.* preload, afterload and contractility. Moreover, pathologies which affect the fibers architecture and cardiac geometry were proved to alter the cardiac torsion pattern. For these reasons, the cardiac torsion represents a sensitive index of ventricular performance (Marcelli et al., 2007, 2008; Rssel et al., 2009; Esch and Warburton, 2009; Cutrì et al., 2010). The assessment of cardiac torsion as a sensitive clinical index led to a substantial increase of the number of experimental and clinical studies aimed at quantifying this parameter. The relevant improvement of the imaging techniques in the last 20 years strongly supported this trend. Different methods have been used to measure the experimental parameters characterizing the torsional behavior (e.g. angular velocity, rotation angle); the first approaches used radiographic tracking of myocardial markers (Ingels et al., 1975, 1989; Hansen et al., 1987, 1991; Moon et al., 1994; Tibayan et al., 2002a,b), optical devices (Kroeker et al., 1993, 1995; Knudtson et al., 1997) and two-dimensional echocardiography (Mirro et al., 1979; Arts et al., 1984). Lately, tissue-tagging magnetic resonance imaging (tagged MRI) has permitted to obtain non-invasive measurement of myocardial deformation in three-dimensional space and prompted investigation of left ventricle torsion (Moore et al., 2000; Lorenz et al., 2000; Miller, 1991; Sandstede et al., 2002; Buchalter et al., 1994, 1990; Maier et al., 1992; Dong et al., 1999, 2001; Setser et al., 2003; Nagel et al., 2000; Notomi et al., 2005; Fuchs et al., 2004; Chung et al., 2006; Gotte et al., 2006; Zwanenburg et al., 2003). Doppler tissue imaging (DTI) has been also proposed as an efficient non-invasive method for quantifying left ventricular torsion in humans (Notomi et al., 2005), thanks to its higher temporal resolution with respect to MRI in the measurement of myocardial velocity. More recently, speckle tracking imaging (STI) technique, based on the appearance of speckle patterns within the tissue during two-dimensional ultrasound imaging, was used to estimate angle displacement respect to the central axis of the left ventricle (Notomi et al., 2005; Helle-Valle et al., 2005). Since all these non-invasive techniques are not suitable for chronic monitoring of left ventricle dynamics, a Coriolis-force based gyroscopic sensor was proposed by our research group as an alternative technique to continuously quantify in vivo Left Ventricle (LV) torsion (Marcelli et al., 2005, 2007, 2008). For a review on the clinical relevance of cardiac torsion, the reader is referred to Shaw et al. (2008). In this context, a model able to reproduce the cardiac torsion pattern in both physiological and pathological conditions may provide important clinical indications. Several models have been proposed in the literature to investigate cardiac torsion using a simplified geometry (Arts et al., 1979; Taber et al., 1996; Kroon et al., 2008; Grosberg and Gharib, 2009; Bagnoli et al., 2011). More complex models were developed to investigate different aspects of heart behaviour (*i.e.*, electrical-mechanical behaviour (Kerckhoffs et al., 2003a,b; Nash and Panfilov, 2004; Kerekhoffs et al., 2005; Nickerson et al., 2005; Xia et al., 2005; Niederer and Smith, 2008; Aguado-Sierra et al., 2011), fluid dynamics (Kovcs et al., 2001; Domenichini et al., 2005; Doenst et al., 2009) and mechanics (Hunter et al., 1998; Nash and Hunter, 2000)) or to study pathological conditions (Krishnamurthy et al., 2013; Meoli et al., 2015) but the cardiac torsion was only qualitatively evaluated. The aim of this work is to provide further insight into the physiological and pathological alterations of the cardiac torsion by means of computational analyses, combining a structural model of the two ventricles with simple lumped parameter models of both the systemic and the pulmonary circulations. Different clinical conditions were simulated to investigate the sensitivity of the cardiac torsion as an index of heart functioning compared to other quantities usually considered in the clinical practice, like the global cardiac hemodynamic parameters, or frequently investigated by computational studies, like the stress and strain distribution in the ventricular wall.

2. Methods

The biventricular computational model presented in this study consists of (i) an anatomy based geometrical model, (ii) a finite element (FE) model of the cardiac mechanics accounting for both the active and the passive behaviour of the myocardium and (iii) two simplified lumped parameter models representing the systemic and the pulmonary circulations.

2.1. *Anatomy based geometrical model*

An anatomy-based 3D geometry of the two ventricles was reconstructed by using Amira® 5 (VISAGE IMAGING, Carlsbad, CA, USA) software, which allows the processing of diagnostic images. Magnetic Resonance (MRI) images of the heart of an adult healthy subject at the end of the systolic phase were provided by IRCCS San Donato, Milan, Italy. A manual segmentation of the MRI slices was performed to carefully distinguish between cardiac tissue and surrounding tissues.