Ultrasound in Med. & Biol., Vol. 43, No. 1, pp. 206–217, 2017

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2016.08.017

● *Original Contribution*

EFFECT OF TRANSMURAL EXTENT OF THE SIMULATED INFARCTION IN A LEFT VENTRICULAR MODEL ON DISPLACEMENT AND STRAIN DISTRIBUTION ESTIMATED FROM SYNTHETIC ULTRASONIC DATA

JAKUB ŻMIGRODZKI,* SZYMON CYGAN,* BEATA LEŚNIAK-PLEWIŃSKA,* MIROSŁAW KOWALSKI,[†]
and KRZYSZTOF KAŁUŻYŃSKI*

*Institute of Metrology and Biomedical Engineering, Warsaw University of Technology, Warsaw, Poland; and [†]Institute of Cardiology, Department of Congenital Cardiac Defects, Warsaw, Poland

(*Received* 22 *December* 2015; *revised* 5 *August* 2016; *in final form* 12 *August* 2016)

Abstract—The identification of a sub-endocardial infarction is of major interest in cardiology. This study evaluates the sensitivity of selected measures to the thickness of such an infarction. Synthetic ultrasonic data (long-axis view) of left ventricular models with inclusions were generated using Field II and meshes obtained from finite-element simulations, which also provided the reference for the estimates obtained from ultrasonic data. The displacements, the first and second component of the principal strain (ε_1 and ε_2), and several measures derived from these quantities were estimated. All estimates, except for the poorly estimated ε_2, exhibited sensitivity to the presence and transmurality of the inclusion. The most sensitive was the gradient of the averaged transmural profiles of ε_1, and ε_1 averaged over the area corresponding to the transmural inclusion. The inflection point of the ε_1 profile shifted toward the outer wall with increasing thickness of the non-transmural inclusion. (E-mail: k.kaluzynski@mchtr.pw.edu.pl) © 2016 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Left ventricular model, Displacement estimation, Strain estimation, Principal strain, Strain gradient, Sub-endocardial infarction, Synthetic ultrasonic data.**

INTRODUCTION

The structural anisotropy of the left ventricle (LV) wall affects the components of myocardial deformation. Longitudinal LV mechanics is most sensitive to the presence of myocardial disease within the sub-endocardial layer. Unaffected mid-myocardial and epicardial function may result in normal or nearly normal circumferential and twist mechanics. Contrary to the transmural infarction, in the case of sub-endocardial infarction the viability of the cardiac muscle is preserved (Kim et al. 2000). Therefore the distinction between these two types of infarction is important, as one can expect that cardiac contractility would improve after revascularization. Hence the quantitative evaluation of the transmural cardiac deformation distribution could make it possible to estimate the extent of disease and gain insight into the mechanisms of LV dysfunction. Non-invasive studies in humans, based on speckle tracking, indicated the possibility of distinguishing transmural infarction from non-transmural infarction (Chan et al. 2006; Zhang et al. 2005). Studies—mostly invasive—have been conducted to measure the transmural distribution of myocardial deformation in animal models (Ishizu et al. 2010; Waldman et al. 1985). However, data on transmural strain gradient in clinical settings are scarce. Although some manufacturers (GE, Toshiba) have designed post-processing programs for multilayer strain estimation, their approach has not gained widespread clinical acceptance, even though speckle tracking has been found to enable selective assessment of epicardial, mid-wall and endocardial function in both animals (Sakurai et al. 2014; Tee et al. 2015) and humans (Abate et al. 2014; Adamu et al. 2009; Leitman et al. 2010). One of the constraints can be the lack of precise layer definition.

In the previous preliminary simulation study, the possibility of distinguishing a wall with a non-transmural inclusion, which simulates sub-endocardial infarction, from a uniform wall in an LV model was confirmed (Zmigrodzki et al. 2015). The distinction was made on the basis of the first component of the principal strain

---

Address correspondence to: Krzysztof Kałużyński, Institute of Metrology and Biomedical Engineering, Warsaw University of Technology, Boboli 8, 02-525 Warsaw, Poland. E-mail: k.kaluzynski@mchtr.pw.edu.pl

Conflict of interest disclosure: No conflicts were stated.

estimated from synthetic ultrasonic data of the long-axis view (LAX) of the model. The study described here has been extended to two LV models with non-transmural inclusions, a model with a transmural inclusion and a model with a homogenous wall. This study was focused on the effect of the inclusion and its transmurality on displacements and several measures of model deformation, such as components of the principal strain, averaged components of principal strain within the area corresponding to the transmural inclusion and within the entire wall imaged, averaged profiles of the principal strain components within the area corresponding to the transmural inclusion, as well as gradients of these profiles. A high sensitivity for a measure of the extent of the inclusion would indicate that this measure has a high potential for identification/stratification of the transmurality of the sub-endocardial infarction. The accuracy of estimation of these measures was also evaluated, using, as reference, the data obtained from finite-element method (FEM) simulation.

METHODS

Models

Models were based on our former studies (Cygan et al. 2014; Heyde et al. 2012; Leśniak-Plewinska et al. 2010). Briefly, the model mimicking the end-systolic shape of the LV had the form of a half-ellipsoid with 15-mm wall thickness (Fig. 1 left) and 52-mL chamber volume in the undeformed state (Zmigrodzki et al. 2015). A homogenous model, a model with a transmural inclusion and two models with a non-transmural inclusion were designed. The inclusions simulated non-transmural and transmural infarctions and were expected to modify the transmural strain distribution with respect to the homogenous model. The inclusions, created as the intersection of a cylinder with the model wall, had a diameter of 20 mm and were located at the inner side of the wall, 40 mm from the model base (Fig. 1 left). The thicknesses of the non-transmural inclusions were 5 and 10 mm. The volumes of the inclusions with respect to the entire model wall volume were 0.96%, 1.92% and 2.88% for the 5-mm-thick, 10-mm-thick and transmural inclusions, respectively. According to the AHA-17 standard (Cerqueira et al. 2002), a segment in the mid-slice of our ventricular model occupies 6.14% of the entire model wall volume. The transmural inclusion occupies approximately half of this segment volume.

The numerical model of ventricle geometry, created using Autodesk Inventor 2012 software (Autodesk, San Rafael, CA, USA), was exported in CAD format to the FEM software, Abaqus 6.13-3 (Dassault Systèmes Simulia, Providence, RI, USA) (Cygan et al. 2015).

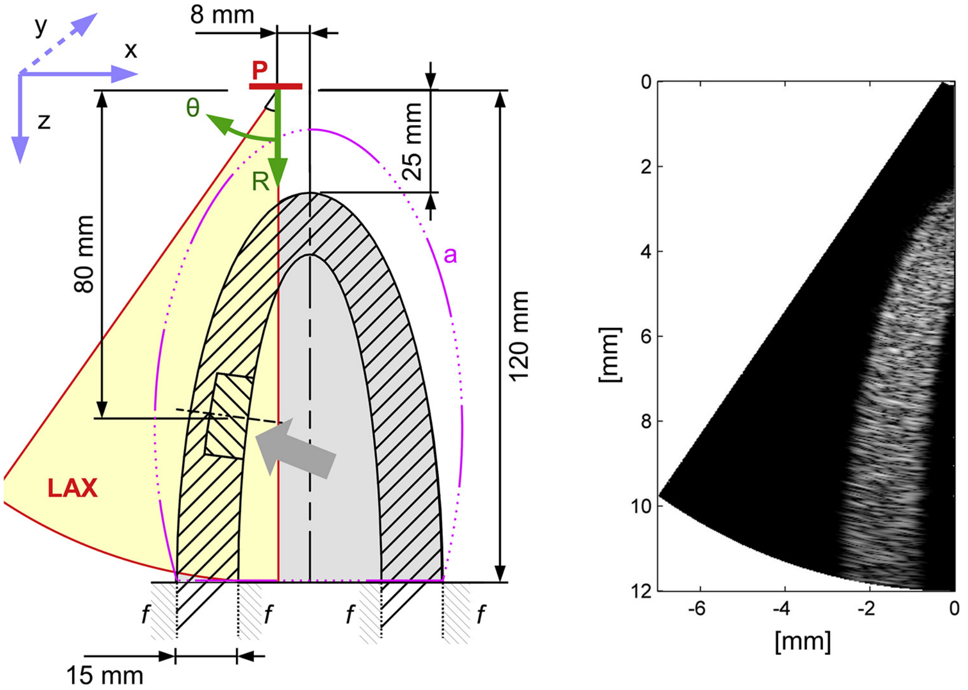

Fig. 1. Left: Schematic view of the sectioned model revealing the location of the 10-mm-thick inclusion (*gray arrow*) and the immobilization areas of the mounting collar (*f*). The maximum displacement of the model outer wall during deformation cycle is marked (*a*, *light magenta*), and the coordinate systems used are shown—Cartesian marked as *x-y-z* in *light blue* and related to the ultrasonic beam with directions: axial *R* and lateral *θ* marked in *green*, elevation is the y-direction of the Cartesian coordinate system. Long-axis view sector marked in yellow with the probe *p* marked in *red*. Right: Resulting synthetic ultrasonic B-mode image of the undeformed model.