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Evaluation of Left Ventricle Phantom by Ultrasound and Multislices Computer Tomography Imaging

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Summary
The main goal of this study was to verify the suitability of sonographic model of the left ventricle (LV) in Computed Tomography (CT) environment and compare radial strain calculations obtained by two different techniques: speckle tracking ultrasonography and Multislices Computed Tomography (MSCT). The Left Ventricular (LF) phantom was fabricate from 10% solution of the poly(vinyl alcohol) (PVA). Our model of the LV was driven by the computer-controlled hydraulic piston Super-Pump (Vivitro Inc., Canada) with adjustable fluid volumes. During cycle of the pump, the Stroke Volume (SV) of water was pumped into the LV phantom and returned to the pump, resulting in changing the inner and outer diameters of the phantom. The stroke volume was set at of 24ml. The fluid pressure was changed within range of 0-60 mmHg, and the pulse rate was equal 60 cycles/per minute. The relationships between computer controlled left ventricular wall deformations and its visualizations of the echocardiographic and CT imaging, both in the normal and pathological conditions were examined. The difference of assessment the Radial Strain between two methods was not exceeding 1.1%.

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1. Introduction

One of the major recent technical developments in ultrasound imaging is the ability to assess tissue deformation. Speckle-tracking echocardiography has recently emerged as a quantitative ultrasound technique for accurately evaluating myocardial deformation by analyzing the motion of speckles identified on routine two dimensional (2D) sonograms. Speckle-tracking echocardiography is potentially suitable for the measurement of angular LV motion because of its angle independence. 2D speckle-tracking echocardiography modality provides new parameters to assess myocardial performance, and these parameters include strain and strain rate. Nevertheless, it has some limitations because the heart moves in three dimensions. The assessment by 2D speckle-tracking echocardiography is based on the measurements of strain calculated on 2D projection only, ignoring the characteristics of three-dimensional (3D) cardiac wall motion. The newly developed 3D speckle tracking has the potential to circumvent these limitations. During the last almost four decades echocardiography has become the most widely applied clinical local and global method of left ventricle functioning assessment by measuring the changes of interior heart dimensions as well as of heart walls contractility. One of the promising tools used during the last decade have been the techniques examining scattered echoes energy while using the unprocessed signal of the ultrasound beam (integrated backscatter) and Doppler assessment of tissue movement – the DTI (Doppler Tissue Imaging) [1], [2]. The first technique limitation

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is the lack of a uniform process of data processing and acquisition from the ultrasound beam. The limitation of the second technique is, as in all Doppler techniques, dependence of acquired values on the angle at which a Doppler beam reflects from moving tissue of the myocardium. Different parameters of DTI and deformation have been examined to give quantitative values to assess LV function. But these techniques have not caused remarkable progress.

From among different techniques used to examine elasticity of biological tissues, the tissue boundaries movement tracking by analyzing the movement of the so called speckle in ultrasound imaging – " speckle tracking "deserves special attention. Bohs and Trahey [3], who in 1991 worked out the two-dimensional method of soft tissue movement measurement using ultrasound, are regarded as forerunners of this technique. In 1993, Ryan, et al. [4] worked out the visualization method of intravascular elasticity of artery walls using rotating high frequency (42 MHz) ultrasound transducer and applying "speckle tracking". However the analysis of artery wall movement was possible not in real time but only after completing the RF signals acquisition.

The authors applied the blood vessel phantom made of gelatine and subjected to intravascular change of pressure from 100 to 120 mmHg for examinations. The method of ultrasound RF signals correlation was applied to examine tissue elasticity apart from the "speckle tracking" method. Berrioz and Pedersen [5] in 1994, applied the correlation method to the ultrasound technique while examining diversified rigidity of model simulating vascular pathologies i.e. walls. atherosclerosis. Chen et al, [6-7] studied the dependence of errors of the '"speckle tracking" method on the influence of different factors connected with the type of tissue examined.

The worked out methods of examining elastic tissue properties were tested on specially prepared models in the form of elastic pipes made of different materials with similar to natural echogenicity ultrasound tissues. At first the mixture of agar and gelatine (in 1997 De Korte et al. [8] and Hall et al. [9]) or polyvinyl alcohol gel (in 2001 Brusseau et al. [10]) were used to build tissue phantoms. These phantoms were however not resistant to considerable pressure changes because they were torn when radial deformations exceeded 5%.

Langeland et al. [11] made the first attempt to apply this type of phantom to assess heart wall deformations in 2003 obtaining linear dependences between longitudinal and transverse strain and their determined estimators with the use of the ultrasound technique and RF signals correlation method.

For almost 7 years the "speckle tracking' technique, which has been widely advertised by the majority of echocardiological equipment manufacturers without giving any details about the technique or even providing essential for diagnostics mathematical expressions, parameters notions and applied to describe elastic heart properties, has had a dominant position in cardiology. Lack of important definitions of measured parameters leads to impossibility of conducting comparative studies using ultrasound scanners of different manufacturers. This problem was noticed only by doctors carrying out examinations in big rich clinics already possessing several older as well as the newest devices.

The support of "speckle tracking" technique is even more inexplicable because it was proven in the work of Tournoux et al. in 2008 [12] that this method is two times worse than the method of tissue contours tracking of ultrasound image.

2. Speckle tracking

Despite the fast development of new scanning machines and new algorithms, the objective method of verification of the results (especially obtained using different scanners) is missing. The main purpose of our work was to develop the mathematical/numerical model and construction of simple phantom of LV deformation with the acoustic properties similar to those measured in the real echography. The basis of the concept of speckle tracking algorithm is a relationship between displacement of heterogeneities of the tissue and the displacement of the resulting speckles in the US image. In this section we present some results obtained using mathematical and numerical modeling of phantom movement and its imaging.

The deformation of the phantom wall and resulting displacements of scatterers are modeled using the basic equations of the theory of elasticity [12] for given boundary conditions. Modeling of the US imaging is based on scattering theory [13]. Both models are integrated, especially in the context of the description of the deformation of the phantom wall, taking into account different distribution of local changes in the density distribution of the phantom material, resulting in the speckles pattern of the ultrasonic image. The scattering in a material indicates that inhomogeneities are the source of secondary, scattered waves, interfering in space. Both, a spatial position of scatterers and their speckle like distribution in US image are random. The deformation of the region with heterogeneities (scatterers) results in change in the position and brightness of the pixel along the image line. Changes in material properties (pathological changes in cardiac muscle) change both, size and spatial distribution of these inhomogeneities.

3. Ultrasound model of the left ventricle

The Left Ventricular (LF) phantom was fabricate from 10% solution of the poly(vinyl alcohol) (PVA). The material used to fabricate the model was suitable for processing. Material used to manufacture the phantom is a 10% (mass) aqueous solution of the PVA (molecular weight 89000-98000, 99+% hydrolyzed, Sigma-Aldrich, St. Louis, MO, USA).

The solution was prepared by dissolving weighted amount of PVA in water at temperature 80-85^{o}C. Magnetic stirrer mixed the solution until PVA became dissolved. In next step the solution was cooled to room temperature and placed in vacuum for one hour to remove air bubbles suspended in the solution. After that, the solution was poured into the mold made from the polymethyl methacrylate. Then the mould was placed in a freezer at -25±0.5^{o}C for 35 hours and then thawed for approximately 40 hours to room temperature. LV phantoms are presented in Fig. 1. The local hardness of the phantom wall, mimmicking the pathological changes, were obtained by drying process.

Fig. 1. The LV phantoms: with stiffened wall imitating the myocardial infarction.

During cycle of the pump, the Stroke Volume (SV) of water was pumped into the LV phantom and returned to the pump, resulting in changing the inner and outer diameters of the phantom.

4. Methods and results

The percentage change of geometry (length, thickness) of examined targets (compared with its initial size) is called the *Lagrangian strain*. The *strain* imaging enable to take segmental measurement of the myocardium strain for the assessment of its local and global functioning. *Strain* describes the relative deformation. *Strain* obtained in the echocardiography were verified *in vitro* and *in vivo* by using various methods. The radial strain (*RS)* is given by maximum in time of the relative change of the internal LV phantom radius:

$$RS \equiv \frac{\Delta R}{R_{Dias}} = \frac{R_{Dias} - R_{Syst}}{R_{Dias}} \quad (3)$$

where:

$R_{Dias} = R_1(t = diastolic\ phase)$

$R_{Syst} = R_1(t = systolic\ phase)$, $R_1(t)$ is an inner radius of the cylinder.

Our new phantom of the left ventricle allows a fully controlled testing of algorithms tracking the dispersion of acoustic markers, as well as improving the existing algorithms or supporting the construction of new ones.

A. Ultrasound Examination:

The setup for elastic properties measurements of the LV phantom is shown in Fig. 2. It consists of the LV model immersed in cylindrical tank filled with water, the hydraulic pump, the ultrasound scanner, the hydraulic pump controller, the pressure measurement system of water inside the LV model and the iMac workstation [14]. The stroke volume could be set within the range of 10-100 ml. The fluid pressure was changed from 0 to 300mmHg, at the frequency of 30-120 cycles per minute. Results of the statistical analysis of dependence of measured elastic parameters of the phantom for two positions of the ultrasound probe: 0 and 25 degree, was performed using the Artida Toshiba unit 3.5 MHz based on the non-parametric U-Mann-Whitney test (the borderline value of the coefficient *p* of significance was set at 0.05). The results showed that both, radial strain, radial strain rate, circumferential strain and circumferential strain rate were independent on the insonifying angle, and pulse rate.

B. CT Examination:

Modern cardiac CT scanning is a fast, noninvasive method with excellent temporal resolution that defines image details. It's primary goal is to rule out significant coronary artery disease. Implementing new dose reduction protocols ensures the dose lower than during invasive coronary angiography. Patient has to hold his breath during scanning in order to eliminate respiratory motion artifacts. Electrocardiogram gating enables to synchronize cardiac cycle phase with CT data acquisition. Diastolic phase associated with the least coronary arteries motion serves as the target phase for coronaries imaging. Cardiac functional analysis requires data from entire cardiac cycle. 64-detector scanner (Discovery CT 750 HD, GE Healthcare, 2012) covers 4cm of cranio-caudal distance every heartbeat. Spatial resolution of the scans is 18,2lp/cm. The comparison of both techniques, ultrasound scanning and CT was performed using Vivid S5 (GE Healthcare) (Fig.3) with 3.5MHz and CT 750 HD 64-slice (GE Healthcare, 2012) machines. In both measurement sessions the PR = 60cycles/minute and the SV = 24ml.

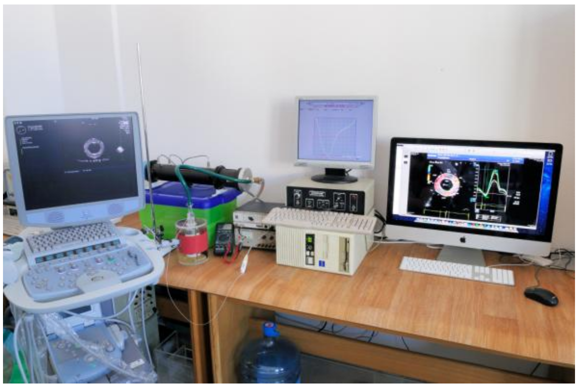

Fig. 2. Setup for elastic properties measurements of the LV model by ultrasound.

For the purpose of the CT scanning LV model was filled with the diluted iodine contrast agent (20% solution of the product Iodixanol 320mgI/ml Visipaque 320, GE Healthcare). Retrospective the ECG-gated MSCT acquisition Discovery CT 750 HD 64-slice (GE Healthcare, 2012) was performed with 0.6 mm slice thickness. The data were reconstructed every 10% of the R-to-R interval of the ECG signal produced by the Vivitro SuperPump control device. The cross-section LV phantom images were obtained using myocardium analysis protocol with manual settings of the valve and the apex. For the Radial Strain examination it was chosen the central part of LV phantom. Under the EchoPack PC software environment, LV model plane was automatically segmented into six segments.

Fig. 3. CT setup for elastic properties measurements of the LV model.

The internal vertical diameter (yellow and violet lines) was taken into account in the Radial Strain analysis.

The value of speckle tracking based the radial strain RS_{st} = 24.6% and the radial strain obtained by the MSCT imaging was RS_{CT} = 23.5%.

5. Discussion and conclusions

Recent studies has shown that MSCT is effective in quantitative analysis of LV strain [14], [15], and [16] MSCT imaging provides excellent isotropic resolution, decreases partial volume effect and motion artifacts what makes it appropriate reference method for echocardiographic measurements. The proposed numerical model and model of the left ventricle are the realization of a fully controlled diagnostic environment, allowing for the testing of algorithms that follow and analyze scattering of speckles, as well as improving the existing algorithms or supporting the construction of new ones. The study indicates the usefulness of the ultrasonographic LV model in the CT technique. The results showed the very good agreement, at the level of 1.1%, in the Radial Strain assessment between speckle tracking technique and the multislice CT examination.

The presented ultrasonographic LV phantom may serve to analyze left ventricle wall strains in physiological as well as pathological conditions [17]. The CT has potential to serve, as reference method, in conducting comparative studies using ultrasound scanners of different manufactures.

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