In Vivo Validation of a 4D Ultrasound Strain Imaging Approach for the Identification of Patient Specific Anisotropic Elastic Material Properties of Abdominal Aortic Aneurysm

Christopher Blase*[1,2], Achim Hegner[1,3], Andreas Wittek[1], Wojciech Derwich[4], Kyriakos Oikonomou[4], Armin Huß[1], and Antonio J. Gámez[3]

[1]Frankfurt University of Applied Sciences – Germany
[2]Goethe University – Germany
[3]Universidad de Cádiz = University of Cádiz – Spain
[4]Frankfurt University Hospital – Germany

Abstract

Introduction:
Biomechanical computational models should be largely patient-specific to provide deeper insight into the pathophysiology of abdominal aortic aneurysms (AAA) and to be relevant for future clinical diagnostics. The identification of individual material properties is of central importance, but they are usually unknown and difficult to determine in vivo. Time resolved 3D ultrasound combined with speckle tracking (4D-US) is a non-invasive imaging technique that provides full-field information of heterogeneous aortic wall strain distributions in vivo. These strains are cyclic strains with respect to diastole. We here present a substantial new development of an in vivo 4D-US strain imaging approach that was presented previously by our group. It identifies the parameters of a nonlinear and anisotropic material equation, while using only information that can be collected in vivo. For this approach we perform an in vivo validation using 6 AAA wall tissue samples harvested from two different patients.

Material and Methods:
Data of two AAA patients (AAA1 and AAA2) presented at the Clinics for Vascular Surgery of the University Hospital Frankfurt am Main were evaluated. 4D-US data was acquired by use of a commercial real-time 3D-echocardiography system, equipped with a 3D transthoracic probe. Diastolic and systolic blood pressures were acquired. After US imaging, in total 6 wall samples (3 longitudinal and 3 circumferential) were harvested from the two AAA patients during open aneurysm repair. All samples were mechanically tested using uniaxial tensile tests, deformations were recorded optically.
On the one hand, specimen deformations were determined from camera images and stress-stretch curves were calculated from wall thickness and recorded force values. The parameters for the anisotropic Holzapfel-Gasser-Ogden (HGO) material equation were identified by fitting to calculated stress-stretch curves of longitudinal and circumferential samples.
On the other hand, for each patient a finite element analysis model was created containing both vessel wall and intraluminal thrombus geometries, which could be segmented independently from the 4D-US images. Measured diastolic/systolic blood pressures were applied to

*Speaker

the lumen surface, reduced axial forces were set to be zero. Upper and lower ends of the vessels were artificially lengthened to achieve more physiological boundary conditions: upper end was clamped and lower end could only move axially (only areas for which US data was available were analysed later). Our newly developed in vivo 4D-US strain imaging approach uses an evolutionary self-adaptive Differential Evolution (JADE) algorithm as optimization strategy. It iteratively calculates the material-dependent load-free geometry and, based on this, the diastolic and systolic geometries using diastolic and systolic blood pressures. Cyclic strains are then calculated with respect to diastole. Parameters for the HGO material equation are identified by minimising an error function that compares cyclic measured wall strains using 4D-US and the calculated cyclic model wall strains.

Results:

For AAA1, comparison of stress-stretch curves calculated using the identified parameters show mean absolute percentage errors (MAPE) in the range MAPE = 0.76-0.07%. For AAA2 MAPE values are in the range MAPE = 0.51%-17.83%.

Conclusion:

We successfully performed an in vivo validation of a new developed in vivo 4D-US strain imaging approach for parameter identification. Results for AAA1 showed good agreement between 4D-US and uniaxial tensile tests. AAA2 had 2 longitudinal and 2 circumferential uniaxial specimens, each identifying the local wall behaviour. The 4D-US method identifies a global material behaviour. If an averaged material behaviour is calculated from the 2 longitudinal and 2 circumferential specimens, this stress-stretch curve agrees well with the stress-stretch curve of the 4D-US method identifying a global material behaviour.