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High Resolution Strain Analysis Comparing Aorta and Abdominal Aortic Aneurysm with Real Time Three Dimensional Speckle Tracking Ultrasound

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WHAT THIS PAPER ADDS

Real time three dimensional (3D) speckle tracking ultrasound allows non-invasive imaging of 3D deformation of the aortic and aneurysm wall with high spatial and temporal resolution. Indices describing heterogeneous wall motion differentiate aortas according to age and pathology (young and healthy adults, older adults with various cardiovascular diseases, and patients with abdominal aortic aneurysm [AAA]). This approach opens a perspective towards individualized characterization of the pathological state of the AAA wall and eventual quantification of abdominal aortic aneurysm rupture risk.

Objective/Background: Ultrasound measurement of aortic diameter for aneurysm screening allows supervision of aneurysm growth. Additional biomechanical analysis of wall motion and aneurysm deformation can supply information about individual elastic properties and the pathological state of the aortic wall. Local aortic wall motion was analyzed through imaged aortic segments according to age and pathology.
Methods: Sixty-five patients were examined with a commercial four dimensional ultrasound system (4D-US). Three groups were defined: patients with normal aortic diameter and younger than 60 years of age ($n = 21$); those with normal aortic diameter and older than 60 years of age ($n = 25$); and those with infrarenal aortic aneurysm ($n = 19$). A diastolic reference shape of aortic wall segments was obtained and local and temporally resolved wall strain was determined. Indices characterizing the resulting wall strain distribution were determined.
Results: The analysis of biomechanical properties displayed increasing heterogeneous and dyssynchronous circumferential strain with increasing patient age. Young patients exhibited higher mean strain amplitude. The distribution of the spatial heterogeneity index and local strain ratio was inversely proportional to age. The maximum local strain amplitude was significantly higher in the young (0.26 $\pm$ 0.17) compared with the old (0.16 $\pm$ 0.07) or aneurysmal aorta (0.16 $\pm$ 0.10). Temporal dyssynchrony significantly differed between young (0.13 $\pm$ 0.10) and old (aneurysmal 0.31 $\pm$ 0.04, non-aneurysmal 0.29 $\pm$ 0.05), regardless of aortic diameter. The spatial heterogeneity index and local strain ratio differentiate non-aneurysmal and aneurysmal aorta, regardless of age.
Conclusions: 4D-US strain imaging enables description of individual wall motion (kinematics) of the infrarenal aorta with high spatial and temporal resolution. Functional differences between young, old, and aneurysmal aorta can be described by mean (circumferential) strain amplitude, the spatial heterogeneity index, and the local strain ratio. Further investigation is required to refine this new perspective of patient individualized characterization of the pathological AAA wall and eventually to rupture risk stratification.

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INTRODUCTION

Infrarenal aortic aneurysm rupture remains a major clinical problem with high overall mortality and morbidity, which can be limited by adequate non-invasive aneurysm screening. Effective aneurysm screening with simultaneous aneurysm rupture risk stratification employing two dimensional ultrasound (US) can contribute to a 42% reduction in abdominal aortic aneurysm (AAA) related deaths.[1] The AAA rupture risk correlates with aneurysm diameter and rises exponentially when a value of 5.5 cm is exceeded. Nevertheless, aneurysm rupture can and does, though rarely, occur (1%) in patients with aneurysms <5 cm.[2] In addition, 26% of patients with an aortic diameter of 25—30 mm develop an aneurysm >54 mm within 10 years, with

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corresponding rupture risk.[3] Therefore, a reliable aneurysm model to predict aneurysm rupture risk is needed.

During the last decades, computational biomechanical models of aortic aneurysms have been developed to obtain patient individual predictors for aneurysm rupture.[4] Aortic diameter, volume and morphology of the intraluminal thrombus, and aneurysm expansion rate have been included in rupture risk analysis.[5–8] Analyzing the biomechanical properties of the aorta with a finite element model allows development of another diagnostic method for risk stratification by defining the rupture prone wall and calculating corresponding parameters such as peak wall stress and peak wall rupture risk.[9]

Prospective risk stratification has been based on offline analysis of computed tomography or magnetic resonance imaging data. Imaging is associated with considerable exposure to radiation and/or contrast medium. The diagnostic risk and potential complications, in the absence of therapeutic use, are not acceptable for prospective aneurysm screening. Moreover, these imaging methods only provide static geometry of the aortic wall. Deformation and wall stress are estimated by computational models based on incomplete information, as important determinants of mechanical behavior, such as wall thickness and individual elastic properties of the wall, are unknown. In contrast, four dimensional US (4D-US) is a radiation free imaging technique, by which not only static three dimensional (3D) geometry, but also wall motion dynamics can be registered. These full field displacement data can be used as additional patient individual information in biomechanical analysis of aneurysms, as well as non-aneurysmal aortas.

4D-US is established for diagnosis of chronic heart failure and for follow up after resynchronization therapy to assess left ventricular contractility.[10–12] The validation study of Bihari et al. comparing 4D-US with laser micrometry and video analysis,[13] together with the biomechanical analysis methods of the 4D-US data by Karatolios et al. and Wittek et al.,[14,15] justify 4D-US for diagnosing infrarenal aorta pathology.

The aim of this study was to evaluate the applicability of 4D-US strain imaging to analyze biomechanical properties of the aorta. Furthermore, the capability of recently proposed indices characterizing 3D wall motion and deformation,[14] to distinguish groups of infrarenal aortas according to age and pathology, was evaluated. The perspective is to use this new diagnostic technique to stratify AAA rupture risk.

PATIENTS AND METHODS

Study group

In a prospective study 92 volunteers, outpatients, or inpatients were examined by 4D-US in the Clinic for Vascular and Endovascular Surgery of the University Hospital Frankfurt/Main from February to December 2013. The study was approved by the local ethics committee; a minimum age of 18 years and written informed consent were the only inclusion criteria. After excluding incomplete investigations, 65 patients with non-aneurysmal and aneurysmal aortas were included for analysis. Nine patients aged <60 years and 10 aged >60 years were examined twice by two investigators in order to determine intra- and inter-observer variability. An aneurysm was defined as an enlarged aortic diameter of >3 cm. Some patients had peripheral arterial disease, which was defined by calf claudication and an ankle brachial index <0.9.

US data acquisition and speckle tracking

All measurements were performed with a customized real time 3D speckle tracking echocardiography (ECG) system (Artida; Toshiba Medical Systems, Otawara, Japan) and a transthoracic 3D ultrasound probe (PST-25SX, 1–4 MHz phased array matrix transducer; Toshiba Medical Systems) as previously described.[14] The mean $\pm$ SD spatial resolution of the data was 0.45 ± 0.13 mm voxel edge length. The frame rate was 21.8 ± 2.2 volumes/s. The mean $\pm$ SD length of the imaged segments of the infrarenal aorta was 36 ± 13 mm (range 12–94 mm). Patients were examined while supine after 5 minutes of rest in this position. Immediately before and after the 4D-US examination, brachial artery systemic blood pressure was measured bilaterally by sphygmomanometry.

The recorded data sets were processed off line using the speckle tracking algorithm provided by the customized Advanced Cardiac Package of the UltraExtend work station (Toshiba Medical Systems) (Fig. 1). The spatial x, y, z coordinates of up to 30×36 matrix points on the luminal surface of the aortic wall were computed for each data volume throughout the cardiac cycle. Measurement tolerance was determined to be ± 0.5 mm,[13] which corresponds to $<\pm 3.3\%$ for a normal aorta with a diameter of 15–20 mm and $<\pm 1\%$ for an aneurysm with a diameter of 5.5 cm. The x, y, z positions of these matrix points over one pulse cycle were exported as ASCII files through a customized interface.

Local wall strain and derived indices for characterization of wall motion

Three dimensional geometry was reconstructed from the end diastolic reference frame, as identified by the ECG signal. The imaged wall segment was subdivided into about 864 subsegments with a size of 2 mm^2 in non-aneurysmal aortas and about 14 mm^2 in AAA with diameters of 60 mm. Displacement fields describing the motion of the aortic wall throughout the cardiac cycle were computed (Fig. 2). For each subsegment circumferential strain was computed from reference geometry and displacement as the ratio of length change to reference length. The method is described in detail in Karatolios et al.[14]

The heterogeneous wall motion of aortic segments was described by parameters quantifying magnitude, spatial and temporal distribution (Table 1). Local circumferential wall strain (CWS) was calculated for each subsegment and each temporal frame with reference to the end diastolic configuration. This resulted in a distribution of local wall strain values for each time interval throughout the cardiac cycle.