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Regional distribution of circumferential residual strains in the human aorta according to age and gender

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ABSTRACT

The biomechanical response of the human aorta varies with axial location, but little is known about the respective variation of residual strains. Such data are available for common lab animals, but in the traditional opening angle measurement the aorta is considered as an ideal cylinder and average residual strains are measured, so that the spatial variations of local residual strains are not determined. The present study provides opening angle and residual strain data throughout the course and around the circumference of the aorta harvested during autopsy. Opening angle showed notable topographical variation; the highest value was at the top of aortic arch, declining abruptly toward the ascending aorta and to a near-constant value in the descending aorta, and rising in the abdominal aorta. The variation of curvature and of external but not internal residual stretch resembled that of opening angle. Extensive residual stress and wall thickness differences were evidenced among quadrants, with the more pre-stressed being also the thicker quadrants. Gender had overall minor effects, but aging led to increased parameters, occurring earlier in the distal aorta but at later stages becoming predominant proximally. Differences in caliber were pronounced in older subjects, unlike those in opening angle, residual stretches, and thickness that were striking in middle-aged subjects. By contrast, curvature decreased with aging in relation to the smaller percentwise opening angle differences. Detailed knowledge of the zero-stress/no-load geometry of the human aortic wall is critical for an in-depth understanding of aortic physiology, while providing the basis for comparison with disease.

1. Introduction

The aorta is not merely a conduit of blood, but an organ that undertakes important roles in culminating the pulsatile flow originating from the left ventricle. The aorta receives and stores the left ventricular ejection volume during systole and releases it to the periphery during diastole, thereby maintaining continuous blood flow, adequate myocardial perfusion, and normal arterial pressure (Boudoulas and Wooley, 1996; Nichols, O'Rourke, and Vlachopoulos, 2011). The structural integrity and storage capacity of the aorta are directly related to the biomechanical properties of the wall. Any factor that reduces the elasticity of the aorta simultaneously impairs its structural integrity and storage capacity, with unfavorable implications for the systemic circulation.

Toward this end, the existence of circumferential residual strains demonstrated independently in the pioneering studies by Vaishnav and Vossoughi (1983) and Fung (1984) has major physiological consequences; see also (Chuong and Fung, 1986; Vaishnav and Vossoughi, 1987). The small residual strains between the no-load state, i.e. when the blood pressure and axial tethering loads are removed, and the zero-stress state homogenize the *in vivo* transmural stress-strain distributions that control the micromechanical milieu in which vascular cells reside and enhance the compliance of the aortic wall, because the latter is dependent on the level of applied stress; reference is made to the seminal papers by Fung (1991) and by Rachev and Greenwald (2003), and to the classic biomechanics textbook by Humphrey (2002). By diminishing the stress gradients across the wall thickness, residual strains also serve as a protective mechanism against aortic dissection or full rupture, namely complete loss of structural integrity of the aortic wall (Sokolis, 2015). Furthermore, residual strain changes are driven by growth/remodeling, so that information on such changes is needed in experimental studies of structural remodeling and for validation of growth/remodeling theories (Alford et al., 2008; Alford and Taber, 2008).

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The distribution of circumferential residual strains, as characterized by the opening angle measurement, has been studied along the length of the aorta in animal models during the last three decades. The first such data were reported by Liu and Fung (1988) for the rat aorta, accompanied by reports about the porcine (Han and Fung, 1991), rabbit (Hong et al., 1997), and mouse aorta (Guo et al., 2002). Species differences have been indicated on an otherwise similar pattern of opening angle change, with the highest values in the ascending aorta, declining along the descending thoracic aorta, and increasing again in the abdominal aorta. Surprisingly little is known about the human aorta and only few anatomical sites have been studied (Saini et al., 1995), documenting a modest increase in opening angle across its length, i.e. not the trend seen in common lab animals. On the other hand, evidence has been submitted for the existence in the human ascending aorta of quadrant-specific variations in residual strains (Sokolis, 2015), so that identification of their circumferential distribution at different levels of the aorta is critical for an improved understanding of its biomechanical function.

The principal purpose of the present study was therefore to examine the regional distribution of circumferential residual strains and major morphometric parameters in the human aorta according to age and gender, and in a detailed fashion, that is in all anatomical sites along the length of the vessel and in the four quadrants around its circumference. The detailed knowledge of the zero-stress and no-load states of the human aorta is expected to aid for a more accurate biomechanical analysis of aortic physiology in relation to region, age, and gender.

2. Material and methods

2.1. Autopsy subjects and tissue sampling

Twenty three subjects (12 males and 11 females, average age: 50.0 ± 3.8 years, range: 19 to 81 years), undergoing autopsy at the Department of Forensic Medicine and Toxicology of the University of Athens Medical School, were included in this study. The aortas were dissected from the sinotubular junction to the bifurcation of iliac arteries and excised in one piece within 24 h of death. After gently cleaning adjoining areolar tissues, the aortas were placed into cold 0.9% saline solution (that was put on ice), and transported within 2 h to the Laboratory of Biomechanics of the Biomedical Research Foundation of the Academy of Athens, where they remained at 4 °C for up to 24 h until experimentation. Table 1 lists the clinical data of the study population; subjects with evidence of aortic dissection or a documented diagnosis of connective tissue disorders, such as Marfan syndrome, were excluded. The study protocol was approved from the Ethics Committee of our Institution and informed consent was obtained from the relatives.

2.2. Axial curvature of the aorta in no-load state

The entire aorta from all subjects was immersed in a wash tub filled with 0.9% saline and a digital image was captured with an Olympus camera (model E400; Olympus Optical Co Ltd, Tokyo, Japan); Fig. 1. Following Liu and Fung (1988), the aortic centerline was defined as the locus of centers of the largest circles inscribed inside and tangent to the walls of the aorta in its coronal plane. It was hand traced with the aid of commercial software (Image-Pro Plus v4.5; Media Cybernetics Inc, Silver Spring, MD, USA) and the radius of axial curvature of the aorta in the no-load state was automatically measured throughout the vessel.

2.3. Determination of circumferential zero-stress state

Each aorta was cut into 50–60 ring-shaped specimens (depending on the overall size of the vessel) of ~5-mm-width at different locations along its length to investigate the axial distribution of morphometric parameters, opening angle, and circumferential residual stretches. In 15 aortas, each ring was laid flat on a wet laboratory towel, its width was measured with a digital caliper, and four dots were drawn on its cross section using an ink pen with waterproof ink. These dots were of different colors and were used as guides for delimiting the anterior, right lateral, posterior, and left lateral quadrants of the vessel, allowing examination of the circumferential distribution of residual stretches. The midline of the anterior quadrant was only marked in the first 8 aortas; the circumferential distribution of wall thickness but not of residual stretches was examined in those rings, as the limits of the different quadrants were not accurately discerned based on optical criteria. Note also that the near cylindrical shape of the ascending and descending aorta permitted the resection of successive rings, whereas fewer rings could be resected in the aortic arch because of its curved shape, causing the axial dimension of vessel in the left lateral quadrant to be much shorter than that in the right lateral quadrant. Attempt was

Table 1
Clinical characteristics of the study population.

Subject no.	Age (years)	Gender	Risk factors and comorbidities	Cause of death
1	70	Female	Hypertension, Diabetes	Pulmonary Infection
2	47	Female	Diabetes	Hanging
3	59	Male	Coronary Artery Disease	Myocardial Infarction
4	46	Male	None	Myocardial Infarction
5	68	Male	Coronary Artery Disease, Hypertension, Smoking	Myocardial Infarction
6	77	Female	Hypertension, Diabetes	Chest Injuries, Accident
7	49	Male	Smoking	Throat Cancer
8	39	Male	Smoking	Drug Overdose
9	22	Male	None	Traffic Accident
10	54	Male	Coronary Artery Disease, Hypertension, Diabetes, Smoking	Myocardial Infarction
11	34	Male	Smoking	Hanging
12	19	Male	None	Hanging
13	50	Female	None	Ovarian Cancer
14	26	Male	Smoking	Pancreatic Hemorrhagic Necrosis
15	35	Female	Smoking	Leukemia
16	45	Female	Smoking	Cardiac Arrhythmia
17	81	Male	Coronary Artery Disease	Smothering, Homicide
18	60	Female	None	Pulmonary Infection
19	39	Female	Hypertension	Undefined
20	57	Female	None	Anaphylactic Reaction
21	30	Female	Smoking	Cardiac Arrhythmia
22	65	Female	None	Traffic Accident
23	79	Male	Hypertension, Smoking, Diabetes	Hanging