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IRBM ••• (••••) •••–•••

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Original Article

Measurement of the Mechanical Properties of the Human Kidney

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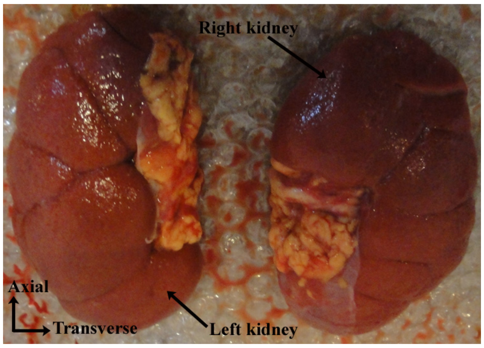
Received 4 March 2017; received in revised form 12 July 2017; accepted 2 August 2017

Highlights

- The mechanical properties of the human kidney were investigated.
- The kidney of 20 male cadavers were excised and subjected to the mechanical loading.
- The elastic modulus and failure stress of the human kidney were calculated.
- Results showed the axial elastic modulus and failure stress of 180.32 and 24.46 kPa.
- Results showed the transversal elastic modulus and failure stress of 95.64 and 31.00 kPa.

Graphical abstract



Abstract

The kidney plays an important role by filtering of all the blood in the body. Mechanical loading as a result of accident or any kind of trauma can disrupt the normal function of the kidney. Since the abdominal injuries these days are on the rise, understanding the mechanical response of the kidney, as one of the most important organs in the abdomen, is of great interest to design of protective equipment as well as preventive measures. Therefore, the precise reliable mechanical properties of the human kidney are a crucial tool for the biomechanical analyses of such conditions. However, so far almost all the reported results on the mechanical properties of the kidney are related to the animals and there is a paucity of knowledge on the mechanical properties of the human kidney. Hence, this study was aimed at experimentally measuring the axial and transversal mechanical properties of the human kidney under the tensile loading. To do that, the kidney of 20 human cadavers was excised during the autopsy and histologically analyzed to extract the mean angle of collagen fibers. Thereafter, the samples were cut and subjected to a series of axial and transversal tensile loadings. The results revealed the tensile elastic modulus of 180.32 ± 11.11 kPa (Mean ± SD) and 95.64 ± 9.39 kPa under the axial and transversal loadings, respectively. Correspondingly, the maximum/failure stresses of 24.46 ± 3.14 kPa and 31.00 ± 5.06 kPa were observed under the axial and transversal loadings, respectively. The kidney showed a significantly ($p < 0.01$, post hoc Scheffe method) higher elastic modulus under the axial loading compared to the transverse one. In addition, a significantly ($p < 0.05$, post hoc Scheffe method) higher maximum/failure stress was observed under the transverse loading compared to the axial one. The findings of the current study have implications

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http://dx.doi.org/10.1016/j.irbm.2017.08.001

Please cite this article in press as: Karimi A, Shojaei A. Measurement of the Mechanical Properties of the Human Kidney. IRBM (2017), http://dx.doi.org/10.1016/j.irbm.2017.08.001

not only for understanding the mechanical properties of the human kidney tissue under axial and transversal tensile loadings, but also for providing a raw data for both the doctors and engineers to be used for diagnosis and simulation purposes as well as tissue engineering.

Keywords: Kidney; Histology; Axial and transversal loadings; Mechanical properties; Elastic modulus

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1. Introduction

The kidneys are located in the abdominal cavity on each side of the spine [1]. Due to the anatomical location of the kidney, it is vulnerable to the sudden impact loading as a consequence of different traumas, i.e., sports-related, accidents, etc., [2–4]. Such trauma impacts subject the kidney to the series of directional loadings which need to be investigated in order to prevent or at least minimize the injury to that. In one hand, any kind of mechanical deformation in the kidney can alter its function in the body and, as a result, trigger complicated malfunctions of other organs. On the other hand, understanding the mechanical properties of the kidney would help to figure out its strength under various loading conditions to provide a suitable threshold value for the diagnosis purposes. However, so far the available mechanical data whether reported for the animals or have not considered the directional mechanical properties of the kidney under the axial and transversal loadings [5,6].

Mechanical loading of soft biological tissues, such as the kidney, not only is involved in development and maintenance of normal function but also in degenerative or injurious conditions where the loading exceeds acceptable levels, e.g., traumatic injuries [7]. In terms of the injury to the soft biological tissues, understanding the mechanical behavior of the tissues is of great importance for the design of protective equipment, and preventative measures. Snedeker et al. measured the *in vivo* ultimate stress and strain of the human and animal kidneys through the aspiration experiments [5]. Another study measured the mechanical properties of the porcine kidney [6]. Nava et al. [8] proposed an experimental approach to quantitatively measure the *in vivo* mechanical behavior of the human kidney. In their method a small vacuumed tube sucked the tissue into that which was equipped with a pressure sensor. Meanwhile, a camera recorded the images of the aspirated tissue. The images were then processed to calculate the mechanical properties of the kidney through the fitting of uniaxial and continuum mechanics models. Whilst the aspiration test device is suitable for in vivo applications, as such organs in the body contains the blood flow the *in vivo* mechanical data might significantly affected by the rheology and perfusion of the blood [9,10]. Therefore, with considering the data so far it is obvious that there is a paucity of knowledge on the accurate and reliable mechanical properties of the human kidney to be used for various medical and biomechanical applications.

Hence, this study was aimed at performing an *in vitro* experimental study to measure the axial and transversal mechanical properties of the fresh human kidneys under the tensile loading. The mechanical data were then reported as the elastic modulus as well as the failure/maximum stress under both the axial and transversal loadings.

2. Materials and methods

2.1. Kidney tissue preparation

After getting the consent from the donor's family under the ethical rule adhered to the declaration of the Helsinki in 2008 as well as Baghyatallah University of Medical Sciences, twenty kidneys from human cadavers were excised for the mechanical measurements as displayed in Fig. 1(a). The mean age of the donors was 68.15 ± 10.22 years old. The reason of death among the donors were all related to the diseases which have nothing to do with kidney, such as the cancer, heart attack, trauma, etc.

2.2. Histology

The excised tissues from the cadavers were interleaved into a 4% buffered formaldehyde solution (pH 7:4) for fixation and further histological examination. Tissue samples were tried to keep their planar geometry and partitioned consecutively at 3 μm in tangential orientation in a way that the fiber orientations of axial and transversal directions. Due to a planar sectioning (the intersection of a body in three-dimensional space with a plane; cutting a tissue in a plane), the in-plane fiber orientations were observed. The histological image of the kidney tissue is exhibited in Fig. 1(b). Black lines indicate the mean fiber orientation characterized by α. A skilled histopathologist measured the orientation of at least 17 representative collagen fibers in the kidney tissue per specimen from the histological images using Olympus Stream Image Analysis software (OSIA). This software can easily and accurately with less than 0.5% error calculate the angle of each fiber component on the histological images. Mean fiber angles and standard deviations were determined by assuming normal distribution and symmetrical arrangement with respect to the transversal direction.

2.3. Mechanical measurements

After the death of the individuals the kidney was excised form the body as presented in Fig. 1(a) and kept into a special package made for transporting of the transplanted organs at 4 °C. The kidney was transported into the mechanical testing laboratory and washed by solution of 0.90% w/v of NaCl with the temperature of 4–5 °C to remove the blood. Using the surgical scalpel, the tissues were cut into the proper size for the tensile and compressive testing. The tissue samples were cut along the axial and transversal directions to help us measure