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ORIGINAL ARTICLE

Uniaxial mechanical behavior of the human female bladder

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Abstract
Introduction and hypothesis The objective of the present study was to investigate the tensile biomechanical properties of the human female bladder.
Methods Tissue samples were obtained from 13 cadavers without pelvic floor dysfunctions. We performed uniaxial tensile tests to measure the stiffness and maximum stress of the bladder tissue. Correlations were calculated using the Pearson correlation coefficient.
Results The bladder tissue stiffness ranged from 1 to 4.1 MPa (mean stiffness, 1.9±0.2 MPa) and the maximum stress ranged from 0.5 to 2.6 MPa (mean maximum stress, 0.9±0.1 MPa). There was a strong positive correlation between stiffness and maximum stress in the bladder tissue (ρ=0.829, p<0.001). Tissue from women younger than 50 years presented higher bladder stiffness than did tissue from older subjects (2.1±0.2 versus 1.3±0.1 MPa, p=0.02). Maximum bladder stress, however, was not associated with age (1.0±0.2 versus 0.7±0.1 MPa, p=0.349). In addition, body mass index and menopausal status were not associated with these biomechanical properties.
Conclusions Age may influence the uniaxial mechanical behavior of the human female bladder.

Keywords Biomechanical properties · Bladder · Elasticity · Mechanical tests · Stiffness

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Introduction

The lower urinary tract has two essential functions: the low-pressure storage of urine in a continent reservoir and the timely expulsion of stored urine in a coordinated, efficient, and complete manner. The bladder is considered the most important and most active part of the lower urinary tract [1]. Normal voiding implies the ability to quickly and completely empty the bladder when it is full. This is achieved by an initial (voluntary) reduction in intraurethral pressure (i.e., urethral relaxation). This is generally followed by a continuous detrusor contraction that leads to complete bladder emptying within a normal time span [2].

Voiding dysfunction can be caused by neurologic disease or injury, a side effect of medical therapy, a disturbance of anatomical relationships within the pelvis and urinary organs, and normal aging. Voiding dysfunction is also affected by changes in the viscoelastic properties of the bladder wall [3].

Biomechanics is the application of mechanics (e.g., concepts of force, motion, stress, deformation) to biological systems. Biomechanics research has helped provide a more thorough understanding of normal tissue function, the effect of pathology, and the impact of treatment in a variety of body systems. Although there is a significant amount of published literature on the management of voiding dysfunction, there is relatively little research on the biomechanical properties of the detrusor muscle. The biomechanical assessment of bladder tissue is important because it will provide clinicians with more knowledge about voiding dysfunction, which could improve clinical outcomes. Moreover, understanding what actually happens when voiding dysfunction occurs is an important step toward the improvement of therapeutics. The purpose of the present study was to investigate the tensile biomechanical properties of female bladder tissues. We investigated the factors that influenced bladder stiffness and maximum stress using uniaxial tensile tests.

Methods

The local research and ethics committee approved the study protocol.

Bladder tissue was collected from 13 female cadavers without observable clinical pelvic floor dysfunctions. The women were between 18 and 65 years old at death (mean age, 45.1±3.0 years). The samples were taken in agreement with a procedure approved by the direction board of the Forensic Pathology Service of the North Branch of National Institute of Legal Medicine, I.P.

The mean parity of the cadavers was 0.8±0.2 (range, 0–2). The cadavers were not formalized, but they were refrigerated at 5°C in a saline solution bath for preservation.

Bladder tissue samples

Tissue samples were collected at the end of normal forensic autopsy procedures. They were dissected from the bladder dome; the approximate dimensions of the tissues were 2× 1 cm. They were preserved in a saline solution bath and kept at 5°C until 15 min before the mechanical tests were performed. The storage time of the soft tissues (until testing) did not exceed 6 h (storage time was <4 h for most samples).

Stiffness and maximum stress assessment

The geometrical properties were acquired through digital image analysis. Two USB webcams were connected to the data acquisition PC to capture front and side view shots, which allowed us to measure specimen dimensions with ImageJ software.

The biomechanical properties were evaluated by means of uniaxial tension tests in the longitudinal and transversal axes. To perform the tests, the tissue specimens were assembled on the testing machine using an assembly support made from high-density polymer. The testing machine was designed for the analysis of soft tissues (Fig. 1). A previous study validated the mechanical testing process for different hyperelastic materials [4]. The load (N) and displacement (mm) data were acquired using a load cell (F_{max}=200 N) and a displacement sensor. A constant displacement rate of 5 mm/min was maintained throughout all tests. Both load and displacement data were recorded until complete specimen rupture. One of the webcams previously employed for the geometry measurement was used to make a video recording of each mechanical test. This procedure enabled the quality control of each test by a posteriori elimination of tests where an inadequate alignment or slippage was detected.

The biomechanical properties examined in the present study were stiffness and maximum stress (Fig. 2). Stiffness is also called the modulus of elasticity, which is a measure of a material's resistance to elastic deformation. This means that for the same given stress (σ), a stiffer material has a higher modulus (i.e., the resulting stretch is smaller) [5]. Human tissue presents a nonlinear mechanical behavior (i.e., a nonlinear relation between force and displacement) [6]. The maximum stress is also known as ultimate stress, which is the stress limit before sample rupture.

Statistical analysis

The statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) software program version 16.0 (SPSS Inc., Chicago, IL, USA). Normal distribution of the data was verified using the Kolmogorov–Smirnov and Shapiro–Wilk tests. The variables were presented as the mean±SEM along with their respective ranges. The statistical differences between the groups were tested using Student's unpaired t test and correlations were calculated using the Pearson correlation coefficient. The significance level was established as $p<0.05$.

Results

Bladder tissue stiffness ranged from 1 to 4.1 MPa (mean, 1.9±0.2 MPa) and maximum stress ranged from

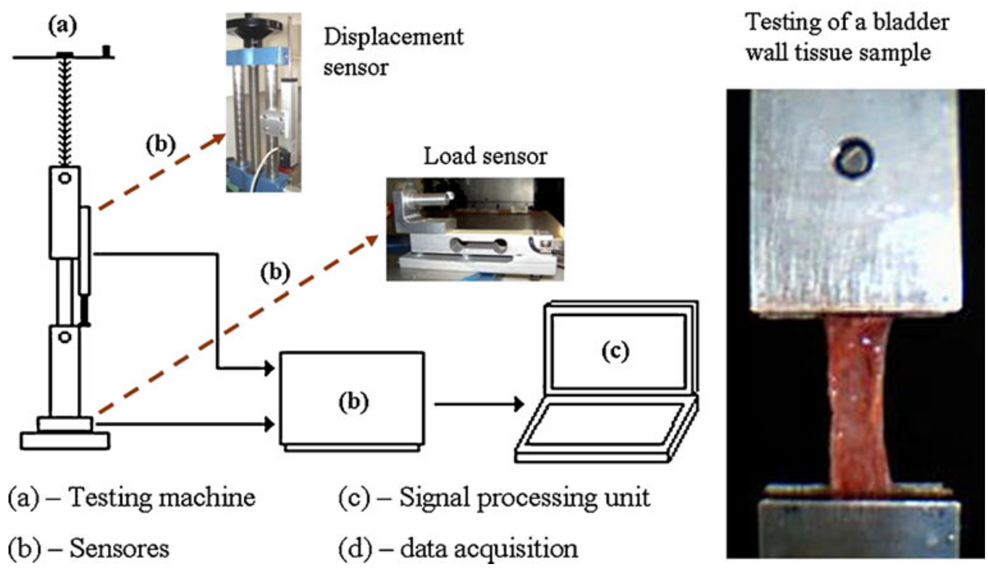

Fig. 1 Uniaxial tension test for the assessment of biomechanical properties of bladder tissue

0.5 to 2.6 MPa (mean, 0.9±0.1). There was a strong positive correlation between stiffness and maximum stress in the bladder tissue (ρ=0.829, p<0.001; Figs. 2 and 3).

We performed a univariate analysis of some of the factors (based on the available data) that may influence stiffness and maximum stress in the female bladder tissue (Table 1). Although we found that tissue from women younger than 50 years presented higher bladder stiffness than did tissue from older subjects (2.1±0.2 versus 1.3±0.1 MPa, p=0.02), the maximum stress was not associated with age (1.0±0.2 versus 0.7±0.1 MPa, p=0.349). In addition, body mass index and menopausal status were not associated with the biomechanical properties of the bladder tissue.

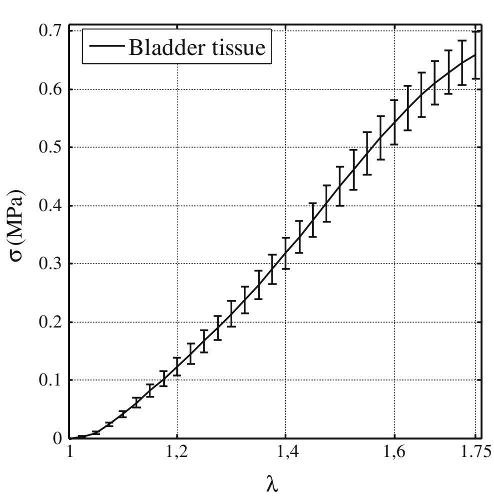

Fig. 2 Typical mechanical behavior for bladder tissue

Discussion

Although the female pelvis comprises one of the most complex regions of human anatomy, this region remains understudied from a biomechanical perspective [7]. There are several studies evaluating the biomechanical properties of female pelvic tissues [8–12], but we are not aware of investigations concerning the biomechanical properties of bladder tissue. In the present study, we evaluated bladder stiffness and maximum stress, which are mechanical parameters used to characterize the uniaxial tension state. A translation of biomechanics research to clinical practice may improve the assessment and treatment of voiding dysfunctions.

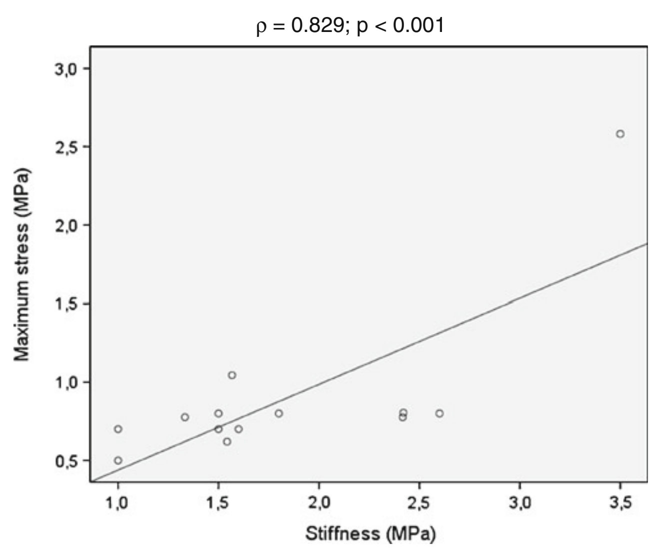

Fig. 3 Correlation between stiffness and maximum stress in the human female bladder. Correlations were calculated using the Pearson correlation coefficient

Table 1 Univariate analysis of the factors that could influence stiffness and maximum stress in human female bladder tissue

Variable	Bladder tissue			
	Stiffness (MPa)	*p*	Maximum stress (MPa)	*p*
Age				
<50 years (*n*=5)	2.1±0.2	0.027	1.0±0.2	0.349
≥50 years (*n*=8)	1.3±0.1		0.7±0.1	
BMI				
<25 kg/m^2 (*n*=7)	1.9±0.4	0.893	0.8±0.1	0.492
≥25 kg/m^2 (*n*=6)	2.0±0.4		1.0±0.1	
Menopause				
No (*n*=6)	1.7±0.4	0.405	0.8±0.1	0.660
Yes (*n*=7)	2.3±0.5		1.1±0.4	

Differences between groups were assessed by unpaired Student's *t* test

BMI body mass index

In the present study, bladder tissue from younger women demonstrated higher bladder stiffness compared with tissue from older subjects. This evidence suggests that bladder stiffness decreases with age. Interestingly, the prevalence of lower urinary tract symptoms increases with age. In addition, age has been linked to the presence of abnormalities in detrusor microstructure patterns [13]. These structural and functional tissue changes that occur with aging have been associated with altered bladder function [2].

According to the International Continence Society, voiding dysfunction is defined as abnormally slow and/or incomplete micturition. Abnormally slow urine flow rates and abnormally high post-void residuals are the basis of a voiding dysfunction diagnosis [14]. Voiding dysfunction can be a result of neurologic disease or injury, a side effect of medical therapy, or a disturbance of anatomical relationships within the pelvis and urinary organs. Moreover, voiding dysfunction can be a result of normal aging, and it is affected by changes in the viscoelastic properties of the bladder wall [3].

Detrusor underactivity is defined as a contraction of reduced strength and/or duration, which results in prolonged bladder emptying and/or failure to achieve complete bladder emptying within a normal period of time [14]. Impaired detrusor contractility has been regarded as the most common cause of detrusor underactivity. Detrusor underactivity affects nearly 3% of adult females, and the symptoms include urinary retention, straining to void, feeling of incomplete bladder emptying, slow stream, and/or incontinence [2, 15].

Because the population is aging, the burden of this illness is a real challenge for all health care systems. Voiding dysfunctions in the elderly are generally multifactorial, and any association with age- or pathology-related changes remains unclear [2]. Some urodynamic data associate the loss of bladder function and voiding efficiency with aging. An increase of post-void residual volume and a decrease of flow rate, average flow rate, voided volume, and bladder capacity have all been correlated with aging [16]. Interestingly, a study evaluating urodynamic parameters in 32 postmenopausal women considered detrusor underactivity a pathological process rather than a natural evolution due to aging [15].

Estrogen hormones are also associated with voiding dysfunction. Estrogen receptors have been identified throughout the nuclei of the connective tissue and smooth muscle cells of the bladder and the urethra [17]. In the present study, however, menopausal status was not associated with the biomechanical properties of bladder tissue.

The present study had several limitations that must be considered when interpreting the results. Ideally, measurements of biomechanical properties would be performed in vivo. Tissue suction and indentation techniques are nondestructive and minimally invasive tests that have been used to evaluate the mechanical properties of human tissues [18, 19]. Feasible animal models (e.g., rabbit, guinea pigs, sheep) have limitations because they are quadrupeds, and the morphology and physiology of their pelvic cavity significantly differs from humans [20]. According to one animal study, freezing vaginal tissue has no consequences on the mechanical response during unidirectional tension testing [12]. Therefore, the refrigeration (5°C in saline solution) of the tissue samples for short periods of time (4–6 h) is assumed to be a suitable storage procedure for preserving the mechanical properties. During the sample collection period (8 months), female cadavers that met the selection criteria were screened via a written questionnaire given to close relatives. Only those cadavers without any known gynecologic problems were considered in the present study. The age interval proved to be an issue because many of the women had been older than 70 when they died. The successful completion of the questionnaire was also a problem as there were many unknowns about the subjects' medical histories. Finally, the mechanical tests were performed within 6 h after sample collection, which made it difficult to coordinate between the forensics team and the mechanical testing team. Therefore, the tests were performed using a restricted number of human cadavers.

The results of the present study suggest that age may influence the uniaxial mechanical behavior of the human female bladder. Further studies are required to evaluate the biomechanical behavior of female pelvic tissues. Biomechanical characterization of female pelvic tissues is an important step toward a more complete understanding of bladder function.

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Conflicts of interest None.

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