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Experimental investigation of the structural behavior of equine urethra

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ABSTRACT

Background and objective: An integrated experimental and computational investigation was developed aiming to provide a methodology for characterizing the structural response of the urethral duct. The investigation provides information that are suitable for the actual comprehension of lower urinary tract mechanical functionality and the optimal design of prosthetic devices.
Methods: Experimental activity entailed the execution of inflation tests performed on segments of horse penile urethras from both proximal and distal regions. Inflation tests were developed imposing different volumes. Each test was performed according to a two-step procedure. The tubular segment was inflated almost instantaneously during the first step, while volume was held constant for about 300 s to allow the development of relaxation processes during the second step. Tests performed on the same specimen were interspersed by 600 s of rest to allow the recovery of the specimen mechanical condition. Results from experimental activities were statistically analyzed and processed by means of a specific mechanical model. Such computational model was developed with the purpose of interpreting the general pressure-volume-time response of biologic tubular structures. The model includes parameters that interpret the elastic and viscous behavior of hollow structures, directly correlated with the results from the experimental activities.
Results: Post-processing of experimental data provided information about the non-linear elastic and time-dependent behavior of the urethral duct. In detail, statistically representative pressure-volume and pressure relaxation curves were identified, and summarized by structural parameters. Considering elastic properties, initial stiffness ranged between 0.677 ± 0.026 kPa and 0.262 ± 0.006 kPa moving from proximal to distal region of penile urethra. Viscous parameters showed typical values of soft biological tissues, as $\tau_1 = 0.153 \pm 0.018$ s, $\tau_2 = 17.458 \pm 1.644$ s and $\tau_1 = 0.201 \pm 0.085$, $\tau_2 = 8.514 \pm 1.379$ s for proximal and distal regions respectively.
Discussion: A general procedure for the mechanical characterization of the urethral duct has been provided. The proposed methodology allows identifying mechanical parameters that properly express the mechanical behavior of the biological tube. The approach is especially suitable for evaluating the influence of degenerative phenomena on the lower urinary tract mechanical functionality. The information are mandatory for the optimal design of potential surgical procedures and devices.

1. Introduction

Dysfunctions of the lower urinary tract are present in both men and women [2,3,22,26] and their social impact is relevant [10,29,31,43]. Surgical repair procedures supported by biomedical devices are nowadays available [8,15,41]. Nevertheless, data regarding the mechanical behavior of biological tissues and structures of the urethral duct have been poorly reported, determining a lack of interpretation about the function of the devices themselves [4,6,17,21,23,27,32,39]. Mechanical information is essential for a proper evaluation of the urethra functionality and a reliable design of prosthetic devices and surgical procedures [7,11,15,20,25,36].

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Table 1
Geometrical conformation of tubular samples for mechanical tests. Median values are reported together with 25th and 75th percentiles.

	Seam to seam length (mm) median [25th 75th]	Internal diameter (proximal extremity) (mm) median [25th 75th]	Internal diameter (distal extremity) (mm) median [25th 75th]	External diameter (proximal extremity) (mm) median [25th 75th]	External diameter (distal extremity) (mm) median [25th 75th]	Internal volume (mm^3) median [25th 75th]
Proximal region	71.24 [55.32 80.27]	7.13 [6.21 8.36]	6.08 [4.72 7.03]	15.37 [14.28 18.19]	13.16 [12.42 14.31]	2.90 [2.60 5.89]
Distal region	65.38 [57.16 98.22]	5.03 [4.79 6.27]	4.06 [3.96 4.21]	13.25 [12.83 14.27]	11.08 [9.76 13.18]	2.45 [2.02 2.54]

With specific regard to the surgical treatment of urinary incontinence, the application of artificial sphincters is a common procedure. Specific reference is made to the male urethra, because of its more complex configuration, but methods can be easily extended to the female urethra. The most widely adopted procedures entail the placement of a cuff around the bulbar urethra [40], the most proximal region of the anterior urethra.

The activities proposed here aimed at defining a procedure for the characterization of the urethra biomechanical behavior. Experimental activities were performed on samples from horse penile urethras. This animal model was selected because of the histological and functional similarity between human anterior urethra and equine penile urethra [9,14,16,18,19,30,37,42,44].

Male urethra is a hollow tube composed of a lumen surrounded by a wall made of different layers [9,38]. With regard to the human anterior urethra, a transitional epithelium surrounds the lumen. Above the epithelium, a layer of dense connective tissue is made of collagen fibers arranged around the lumen perimeter. Above the dense connective tissue layer, loose tissue contains corpora spongiosa, blood vessels and thin connective layers. While very poor percentage of muscular tissue can be found within the human anterior urethra, smooth longitudinal muscular fibers can be found in the proximal region of horse penile urethra [35]. Such fibers mainly contribute to form the extensor muscle of the penis. The passive mechanical properties of the extensor muscle may influence the stiffness of the urethra, while its active functionality plays a different role. The amount of smooth muscular fibers is much larger in the proximal region of the urethra than the distal portion. Mechanical properties of the different layers and mutual interaction phenomena determine the overall mechanical behavior of the composite biological structure. Such a complex configuration leads to a non-linear and time-dependent mechanical response, which can be investigated adopting experimental methods. Mechanical testing of urethral tissues can be performed on different specimen typologies. Aiming at characterizing the overall structural response of the biological system [11,33,34], tests can be performed on tubular segments, as inflation tests [13,25].

The present investigation entails a coupled experimental and computational procedure. The procedure aimed at identifying parameters that interpret the structural behavior of the tubular structure. With specific regard to the experimental activities, inflation tests were performed on equine samples. Inflation tests entailed an almost instantaneous inflation of physiological saline within the tubular structure, up to a specific volume, before holding the volume constant until the end of pressure relaxation phenomena. The specific experimental procedure allowed the evaluation of both the elastic and the time-dependent response of the biological structure. A mechanical model was developed with the purpose of interpreting the mechanical behavior of the tubular structure, accounting for parameters that interpret the corresponding structural elastic and viscous properties. Statistical methods and optimization algorithms allowed the processing of data from experimental activities and the minimization of the discrepancy between model and experimental results. The procedure permitted to identify the statistical distributions of curves and parameters that characterize the urethra structural behavior.

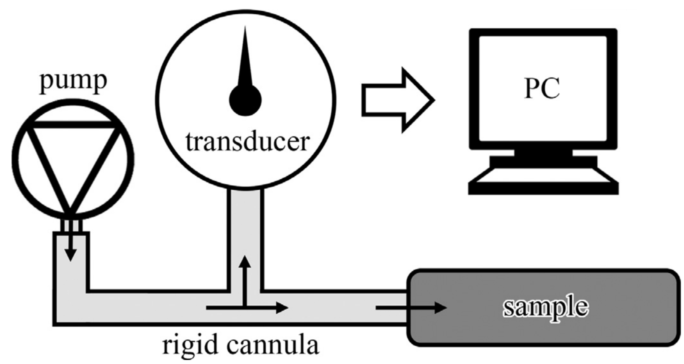

Fig. 1. Schematic representation of the experimental setup. A prescribed volume of physiological saline is stored and a connection with the urethral segment is provided by a rigid cannula. A transducer monitors the pressure data that are transferred for storage.

2. Methods

2.1. Mechanical tests

Experimental tests have been performed on specimens from fresh horse penises. The penises of thirteen male saddle horses (4–11 years old and 300–400 Kg in weight) were collected from a local abattoir, packed in physiological saline (0.9% NaCl) at 4 °C and transported to the laboratory. Penises have been dissected to obtain urethra samples composed of the lumen surrounded by corpora spongiosa. Each urethra was cut and divided in two segments, providing proximal and distal specimens of different lengths, ranging between 140 and 180 mm. Before testing, the internal and external diameters of the sample were measured at both proximal and distal extremities using a digital caliper (Table 1). Mechanical tests have been developed at room temperature of 28° within six hours after sacrificing the animals. Specimens were stored in physiological saline at 4 °C.

Inflation tests were performed using the experimental setup reported in Fig. 1. A pump was connected to the sample by a rigid cannula (4 and 6 mm internal and external diameters, respectively). The proximal extremity of the sample was fixed to the cannula using surgical elastic seam, while the distal extremity was sealed. The seam to seam length was measured using a digital caliper to measure the actual length of the testing region. The cannula was also connected to a transducer (142 pc 01d pressure transducer, Honeywell, USA) for pressure measurement and storage at 10 Hz.

During each inflation test, the sample was firstly inflated at high speed with physiological saline. The imposed volume was subsequently held constant for about 300 s in order to allow the development pressure relaxation phenomena. The sample was finally deflated. The following tests were interspersed by 600 s of rest for the recovery of the initial mechanical conditions. Increasing volumes were inflated for each sample, ranging between 5 and 50 ml. During the test, the external surface of the samples was kept hydrated with physiological saline to prevent drying. Inflated