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Intravesical tunnel length to ureteral diameter ratio insufficiently explains ureterovesical junction competence: A parametric simulation study

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Summary

Objective

In 1959, Paquin recommended a tunnel length five times the diameter of the ureter to prevent vesicoureteral reflux (VUR) during ureteral reimplants. In 1969, Lyon et al. challenged Paquin's conclusions and proposed that the ureteral orifice was more important than the intravesical tunnel for UVJ competence. It is not known if the two mechanisms of UVJ competence (tunnel length and UO spatial orientation) are interdependent or if one is more critical. Although in clinical practice Paquin's rule has stood the test of time, classical mechanics of materials would predict more coaptation (less reflux) with larger diameter ureters and this contradicts Paquin's rule. The aim of this study was to test Paquin's tunnel length theory by parametrically modeling the ureterovesical junction (UVJ) to determine variables critical for ureteral closure.

Study design

LS-DYNA finite-element simulation software was use to model ureteral collapse (Figure). Intravesical tunnel length, ureteral diameter, ureteral thickness and ureteral stiffness were all modeled. Changes in the pressure required to collapse the ureter were studied as each variable was changed on the model. The modeled ureteral orifice was not affected by changes in bladder volume (in a real bladder, bladder distention would pull the ureteral office open) and had no constraints (which could occur by suturing the ureteral orifice to a stiff bladder).

Results

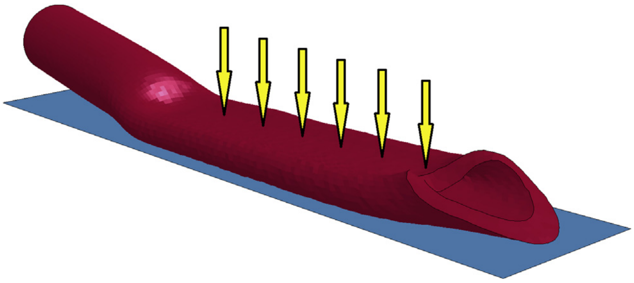
As predicted by classical mechanics of materials, the pressure required to collapse the ureter was inversely related to its diameter. Above 1 cm tunnel length, pressures required to collapse a ureter did not decrease by any significant amount. Increasing ureteral thickness or ureteral stiffness did increase the pressure required to collapse the ureter, but only significantly for ureteral thicknesses not commonly seen in practice (i.e. wall thickness of 2.5 mm in a 6.4 mm ureter).

Discussion

Our model showed that for most ureters seen in clinical practice (3—30 mm in diameter), and when the ureteral orifice is not constrained by the bladder mucosa, a 1 cm tunnel would allow the ureter to collapse under low pressures. Contrary to Paquin's belief, larger diameter ureters collapsed more easily. It is important to understand that our model's main limitation was that it did not study the effects of the ureteral orifice, which in light of our findings must play an important role in preventing reflux as suggested by Lyon et al., in 1969. For example, a 3 cm ureteral orifice sutured to the bladder mucosa would be difficult to collapse as the bladder distends and pulls open the orifice. One way of compensating for a difficult to collapse ureteral orifice would be creating a larger diameter tunnel, but another would be to create a better ureteral orifice, perhaps by narrowing the diameter of the UO (distal ureteral tapering) and making it protrude into the bladder like a volcano (i.e. advancement sutures, or creating an intravesical nipple).

Conclusion

We hope that this new understanding of the variables involved in ureterovesical junction competence can lead to further refinement in our surgical techniques to correct vesicoureteral reflux.



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Introduction

In 1959, Paquin recommended a tunnel length five times the diameter of the ureter to prevent vesicoureteral reflux (VUR) based on a comparison of postmortem specimens of patients with and without VUR [1]. However, Paquin ignored ureteral thickness in his calculation, which, according to classical mechanics of materials, should play a role. He also did not address VUR that may be caused by ureteral orifice spatial orientation, size and stiffness.

In 1969, Lyon et al. [2] challenged Paquin's conclusions and proposed that the ureteral orifice was more important than the intravesical tunnel for UVJ competence.

Current surgical practice acknowledges Paquin's theory as it is still recommended to create a 5:1 tunnel when doing an open ureteral reimplantation. Lyon's theory might come into play when using bulking agents to affect the shape and configuration of the ureteral orifice but is not directly taken into consideration during surgical ureteral reimplants. No one has formally tested these two competing theories of UVJ competence. It is not known if the two mechanisms of UVJ competence (tunnel length and UO spatial orientation) are interdependent or if one is more critical.

Since Paquin and Lyon, little research has looked at variables responsible for the prevention of VUR or leaking from Mitrofanoff type conduits. Watson et al. studied the pressures inside Mitrofanoff conduits in relation to bladder pressures to determine functional profile length, finding a mean 3.4 cm in the continent versus 1.8 cm in the incontinent patients [3], suggesting that longer intravesical tunnels are less likely to reflux.

Ureteral tailoring originated as a consequence of the 5:1 rule, given that there would not be any other way of creating a long enough tunnel on a dilated ureter and still following the rule. A case-control study of megaureter reimplants with and without ureteral tailoring found equivalent outcomes [4], raising concerns about the validity of the 5:1 rule.

The aim of this study was to test Paquin's tunnel length theory by parametrically modeling the ureterovesical junction (UVJ) to determine the variables critical for ureteral closure.

Materials and methods

The purpose of this study was to test the relationship between intravesical tunnel length and VUR by measuring the pressure required to fully collapse the ureter to prevent any fluid passage. Tube collapse is a complex mathematical calculation, where effective tube stiffness is correlated to the tube overall diameter, tube wall thickness, material properties (especially stiffness), internal pressure, external applied pressure and the area on which the pressure acts.

Finite-element analysis software is often used to study stresses and deformations in mechanical components, and is being used increasingly to model human organs, tissues and fluid flow, as models for these materials are developed. Many finite element codes are available, such as Abaqus, ALGOR, Ansys and Nastran. One such computer simulation software is LS-DYNA [5]. LS-DYNA is capable of modeling most physical systems and studying deformation, stress concentrations, force transfer, mass transfer, heat flow and many other variables as long as the material properties, boundary constraints and loading conditions are known or can be reasonably assumed.

LS-DYNA has been used to model several areas of the body. While many simulations have been focused on the forces imparted to internal organs from impacts, other simulations have focused on fluid flow through vessels and tube collapse. In 2013, a simulation was conducted to study neural interactions and large-scale neural tissue mechanics [6]. In 2003, Carmody et al. studied the effects of blood pressure on the deformation of the aortic valve [7]. In 2010, Wenk et al. performed simulations reviewing the reflux of blood through the mitral valve in the left ventricle [8]. This simulation provided grounds for understanding simulated vessel closure. In 2011, a simulation was conducted to study how changing the parameters of the ureter changed the pressure and flow distribution on the ureter during peristalsis [9]. The application of LS-DYNA to systems requiring full lumen closure shows that the program appears suitable for studying ureteral collapse.

Finite element analysis has some benefits over physical testing. In biological materials, the material properties vary greatly from one specimen to another. Also, biological materials may have different properties when analyzed in-situ as opposed to ex-situ. Measurement methods used to determine stresses, strains and pressures can interfere with the biological material's function, causing a false reading. For these reasons, the consistent, controllable, in-depth finite-element model was used.

A thick-walled tube model was created using the LS-DYNA software. Pressure was applied to one side of the tube to collapse it, representing pressure applied to the ureter from the bladder. Ureter collapse was measured under varying dimensional, stiffness and pressure conditions to best replicate the variety of real-world ureters.

Watson et al. studied Mitrofanoff conduits in children, and reviewed closure pressure for various types of tubes [3]. According to that paper, material properties, outside diameter and exposure length are critical to determining whether the tube would fully collapse or if it would leak. However, lumen closure (or partial deflection) is well understood from a mechanics standpoint for stiff engineered materials, and is inversely proportional to wall thickness [10], so it was hypothesized that ureteral wall thickness would likewise play an important role in ureter mechanical behavior.

For the simulation models, there were six outer diameters used: 3 mm, 6.4 mm, 10 mm, 20 mm, 25 mm, and 30 mm (to represent a spectrum from the normal size to the more pathologic ureters). Wall thickness of the ureter was modeled with values varying from 0.2 mm to 4 mm. Some simulations included a lumen pressure of 1.33 cm H_2O, which was the pressure in the ureter used in previous ureter simulation research [9]. The ureter material is viscoelastic, and material properties were obtained from research conducted by Yin and Fung [11] detailing the material properties of the ureter, and the ureter stiffness was modeled using a piecewise function. According to that study,

$$T=(T^{*}+\beta)e^{\alpha(\lambda-\lambda^{*})}-\beta$$