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A Simulation Study of the Effects of Sound Wave upon the Ureteral Peristalsis

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Abstract **-** This paper presents a mathematical model, computing the effects of sound wave propagated during the ureteral peristalsis on the rate of the urine flow through the ureter. This model predicts that by surrounding the UPJ with a biomaterial string, the sound wave generated by the movement of the string during the peristalsis cycle, will increase the urine output by 14 ml per day in a human kidney. The simulation result obtained from this model is compared with respect to the amount of urine drainage in a ureter with a double J stent.

Keywords**:** Ureteral Peristalsis**,** Urine Drainage, Sound Wave

Introduction

The ureter is a smooth tubular muscle, which transports urine from the Kidney's pelvis to the bladder. The passage of urine through the ureter's lumen is regulated by the rhythmic contractions of the ureter wall, called peristalsis [1].

Dysfunctional ureteral peristalsis and urine transport could occur due to traumas, such as hydronephrosis or different obstructions. Following the reversal of the trauma, the common treatment is to place a double J stent inside the ureter's lumen in order to regulate the ureteral peristalsis and bring back the peristaltic cycles to its pre-obstruction level [2].

The purpose of this study is to propose an alternative to the existing double J stent, in order to regulate the ureteral peristalsis and return to healthy ureteral contractions following the reversal of the trauma.

This paper presents a mathematical model that calculates the contraction force of the ureter's wall during the peristalsis cycle, in a healthy human kidney. This mathematical model will show how the ureteral peristalsis cycle could be stretched out in order to increase the volume of urine transported through the ureter. In order to alter the peristalsis cycle and increase the duration of the rhythmic contractions of the ureter's wall, a biomaterial string having the same material properties as a spider silk is attached to the outer layer of the ureter near the pyeloteral junction (UPJ).

During the peristalsis cycle, the ureter's wall is contracted. The contractile force of the ureter's muscle plucks the spider silk string that encircles the ureter near the UPJ. The generated tension by the compressed string will create a transverse sound wave travelling at the opposite direction of the action potential signals. The power liberated by the transverse sound wave will create a twitch at the UPJ. This will keep the junction between the kidney and ureter open for a longer time and elongates the peristalsis cycle, letting a bigger volume of urine to be drained.

Simulation Method

The ureter is prototyped as a cylinder with circular cross section. A thin circular string, having the same material properties as a spider silk is attached to the outer shell of the ureter near the UPJ. The Spider silk is a tough biomaterial, that exhibits properties, such as strength, toughness, elasticity and robustness. The spider silk has a unique combination of high strength and elongation before rupture. [3]. Although, the human ureter is surrounded by fluid at 37^{o}C, in this study, it is assumed that the medium surrounding the ureter is composed of dry air at ambient temperature. It should be noted that the spider silk responds to humidity by super contracting, which becomes more compliant and several times more extensible than dry silk [4].

The transverse sound wave, generated from the release of tension of the spider silk string, is assumed to be a sinusoidal wave of one harmonic.

Mathematical Model

The force generated by the ureter's walls during the ureteral peristalsis cycle is defined by [5]:

$$ActionPoentialPower = \frac{\varphi^2}{R} = Force \times \frac{dx}{dt} \tag{1.a}$$

$$Force = \frac{\varphi^2}{R \times v} \tag{1.b}$$

Where:

v [m/sec] is the conduction velocity of a urine bolus travelling through the ureter's lumen [5].
φ [V] is the Action Potential generated at UPJ, preceding the ureteral peristalsis cycle [5].
R [Ω] is the lump electric resistance of the ureter at UPJ [5].

The time-averaged power of a transverse sinusoidal wave on a string is defined by:

$$Power = P = \frac{1}{2}\mu \times A^2 \times \omega^2 \times V \tag{2}$$

where:
μ [kg/meter] is the mass of the string.
A [meter] is the Amplitude of the transverse sound wave.
ω is the Angular Frequency of the transverse sound wave.
V [meter/sec] is the Propagation Velocity of the transverse sound wave.

The sound wave amplitude is calculated by using the Hook's law:

$$Amplitude = A = \frac{F}{K} \tag{3}$$

where:
F [N] is the force generated by the ureter's walls during the ureteral peristalsis cycle [Eq. 1.a].

K [N/meter] is the spider silk spring constant.

The Propagation Velocity of the transverse sound wave is calculated as [6]:

$$V = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{Force}{\mu}} \tag{4}$$

Where:
T [N] is the tension created on the spider silk string during the ureteral peristalsis cycle. It is assumed that the Tension on the string is equal to the muscle contraction force of the ureter's wall during the peristalsis cycle.
μ [kg/meter] is the mass of the string.

The angular frequency is calculated as:

$$frequency = \frac{V}{\lambda} = \frac{V}{4\pi r} \tag{5.a}$$

$$\omega = 2\pi \times frequency \tag{5.b}$$

Where:
λ [m] is the wavelength of the transverse sinusoidal sound wave, which is equal to twice the length of the string. The length of string is considered to be equal to 2πr.
r [m] is the radius of the ureter.

The Figure 1 below shows a Matlab representation of the above equations. This model computes the contraction force during the peristalsis cycle, as well as the power generated by the transverse sound wave which travels toward the UPJ. The transverse sound wave is created when the ureters' wall smooth muscle is contracted. The tension created on the spider silk string backtracks a sound wave which travels toward the UPJ. The power generated by this reverse signal will allow the UPJ to be remained open longer and allow the output of extra urine volume. through the ureter's lumen. For this simulation, the ureter is considered to have a radius of 3 mm [5]. The tension imposed upon the spider silk string surrounding the outer shell of the ureter near the UPJ is considered to be equal to the ureter's wall contraction muscle force. The spring constant of the spider silk string is considered to be 0.7 [N/meter]. The mass of the spider silk string is considered to be 0.85 [Kg/meter] [7]. The lump electric resistance of the ureter at UPJ is considered to 370 [Ω]. The conduction velocity of a urine bolus travelling through the ureter's lumen is equal to 4.8 [cm/sec] [5]. The action potential signal initiating the peristalsis cycle uses the synthetic model presented in [5]. The wavelength of the transverse sound is calculated as twice the length of the string.

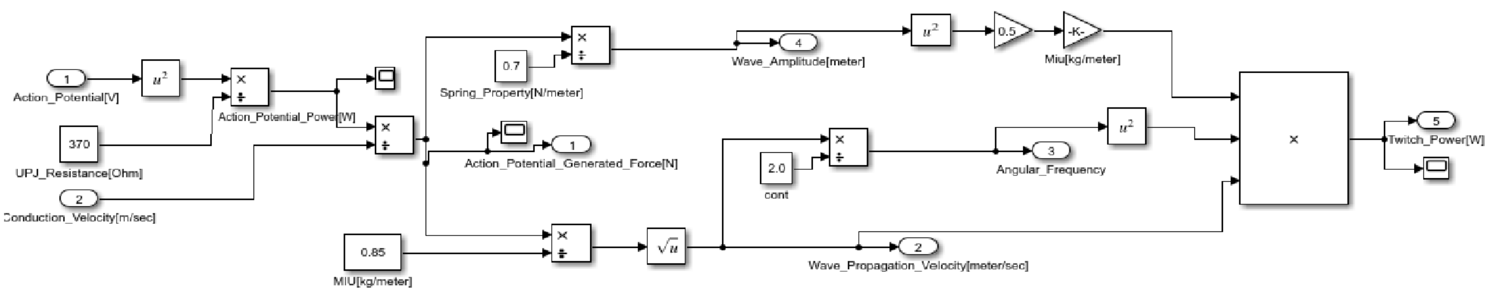

Fig. 1: Simplified representation of the generated twitch power acting on UPJ.

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Result

The model described in Figure 1 was simulated using Matlab Simulink, in order to compute the generated contraction muscle force of the ureter's wall and the twitch power generated by the spider silk during the peristalsis cycle.

Figure 2 shows the computed muscle contraction force of the ureter's wall during the peristalsis cycle. The simulated value of the contraction force is calculated to be 0.5 [mN]. Kymora &al, have measured experimentally the muscular contraction of the ureter's wall during the peristalsis cycle. They have used electric field stimulation in a control ureter. They have measured a urethral contraction force to be 0.7 [mN] [1]. There is a 30% discrepancy between the experimental and the computed simulation data.

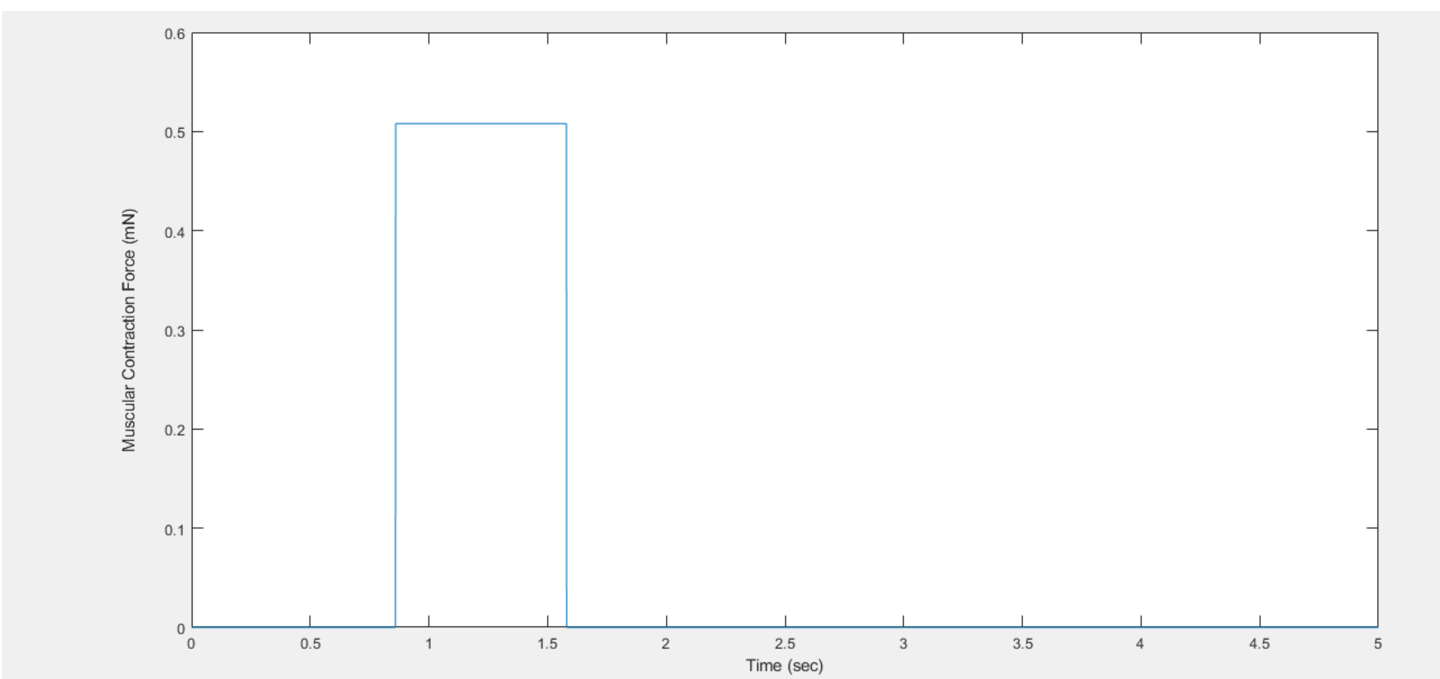

Fig. 2: The Computed Muscle Contraction Force of Ureter's Wall During the Peristalsis Cycle.

Figure 3 shows the power generated by action potential signals, that allows the UPJ to open and the peristalsis cycle to be carried on. This figure shows also, the twitch power released by the transverse sound wave, initiated from the plucked spider silk string encircling the outer layer of the ureter, during the peristalsis cycle. The twitch power that occurs at the end of the peristalsis cycle, enables the UPJ to remain open for an extra 0.01582 second. This allows an extra urine drainage of 14.0 ml per day in a human kidney. Kyung-Wuk & al. Have measured the effects of a double J stent in ureter. The experimental results show that when inserting a double J in a ureter, the urine drainage could be increased up to 66 ml per day in a human kidney [2].

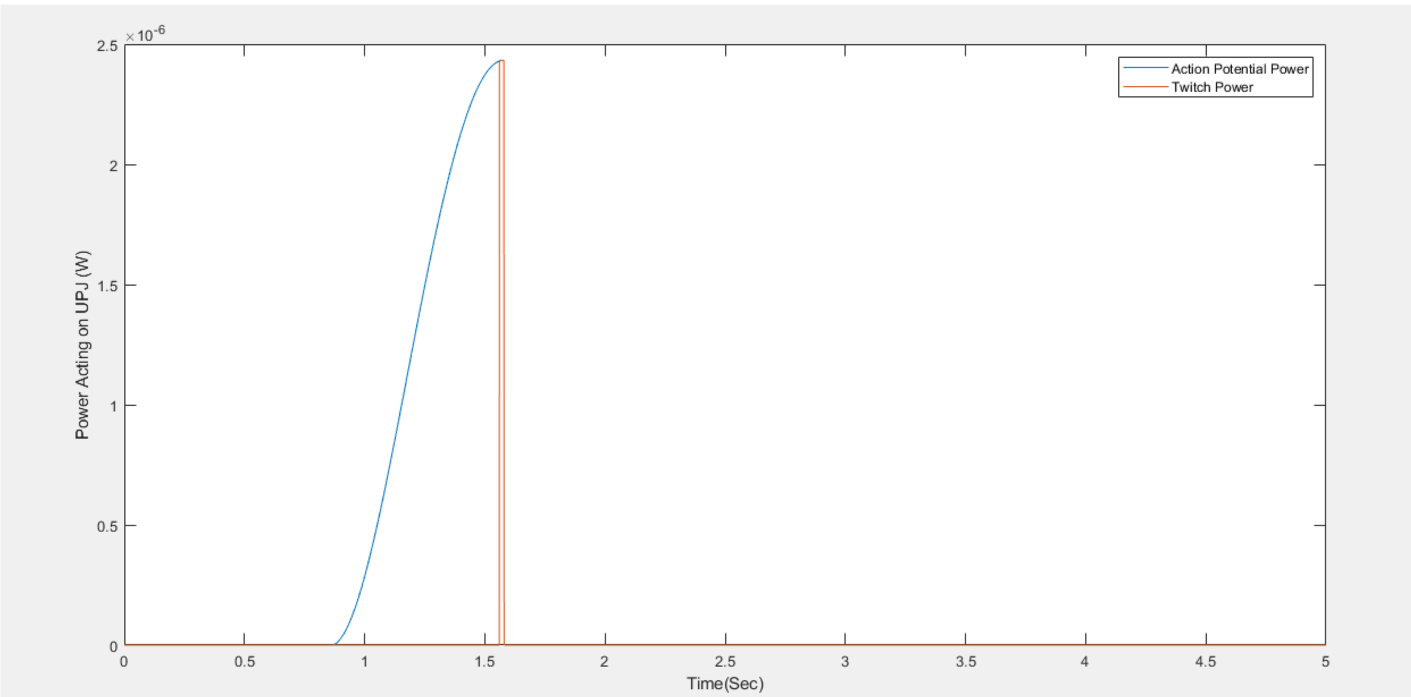

Fig. 3: The Generated Action Potential Power and the Generated Twitch Power.

Conclusion

The ureters serve a vital function in the urinary system, as they transport urine from the kidneys to the bladder. Different traumas could result in ureteral dysfunction, which affects the peristaltic activity and disrupt the urine drainage. [3]. The reversal of the trauma could leave behind side effects that could disrupt the normal process of urine drainage through the ureter. The common treatment to regulate the ureteral peristalsis is to insert a double J stent inside the ureter's lumen.

This study has presented a mathematical model, proposing a simple mechanism of using power released by a single harmonic sound wave, occurring at the end of the peristalsis cycle, in order to regulate the ureteral peristalsis. The simulation result shows that the urine drainage is increased when surrounding the outer layer of the ureter by a thin biomaterial sting.

This new mechanism could be an alternate way to regulate the drainage of urine through the ureter.

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