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A Simulation Study of the Urine Transport Conduction Velocity Through the Ureter

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Abstract - *This paper presents a mathematical model that explains the mechanism behind the drainage of urine from a healthy human kidney through the ureter. Computer simulation is used to study the conduction velocity of a urine bolus through the Ureter lumen. The conduction velocity calculated by the simulation model is 4.8 cm/sec which is in within the range of experimental values of 2 to 6 cm/sec.*

***Keywords*:** Peristalsis, Pacemaker, Electro-mechanical Pump, Conduction Velocity

Introduction

The passage of urine through the ureter's lumen is derived by successive waves of active muscular contraction that pass along its walls from the kidney to bladder. In between contraction waves the muscle of ureteral wall is relaxed [Ref 4]. This phenomenon is called Peristalsis. The Peristalsis is initiated at the renal pelvis following the pacemaker effect generated by the synchronized and rhythmic activity of the sum of action potentials initiated by each nephron [Ref 5]. An action potential is an electric signal that is created from a temporary shift from negative to positive potential of a nephron membrane.

Peristalsis controls the urine flow. Under normal flows, the urine between two contractions waves takes the form of a bolus. The rhythmic contractions of the ureter wall, push through the ureter's lumen the bolus of urine. The mean rate of flow of urine through the ureter is equal to the rate of production of urine by the kidney [Ref 4].

Simulation Method

Assumptions

The kidney is prototyped as a homogeneous volume conductor propagation model. It is considered as an electric load affecting the propagation of the "pacemaker" action potential through the ureter. The Electrical characteristic of the kidney's pelvis is represented in a bulk format. The urine is transported from the kidney's pelvis through the ureter's lumen by the action of pperistalsis and muscular contraction of the ureter wall. This mechanism is modelled as an Electro-mechanical pump whose action is triggered at the pyeloureteral junction (UPJ) when the frequency of peristaltic contractions reaches that of the pacemaker; at this stage, the ureter assumes the form of an open duct. It is assumed that the power generated by the Electro-mechanical pump is a result of the pacemaker effect at UPJ. During the polarization phase of the peacemaker activity, it is assumed that the UPJ is switched opened to let the urine bolus to be evacuated.

Mathematical Model

The mechanical power required to move a bolus of urine through the ureter, is equal to the electric power generated at the Kidney's pelvis.

$$Power = \frac{\Phi^2}{R} = m \cdot g \frac{dx}{dt}$$

Φ is the Sum of Action Potentials at UPJ
R is the lump Resistance at UPJ

m is the mass of a urine bolus
m= ρ * V where ρ is the density of Urine at 37° C, V is the volume of a bolus.
g is the gravitational acceleration
dx/dt is the conduction velocity of the urine bolus travelling the ureter lumen.

Model Assumptions and Parameters Estimation

In order to simulate the effect of the pacemaker, a simulated synthetic wave is used that imitates the morphology of a renal action potential. According to J.R. Cotton [Ref. 1] the Kidney Membrane Action Potential at rest, is -91 mV. There is a slow upstroke velocity of 1 V/sec and an overshoot to approximately +30mV, with an Action Potential duration of approximately 1 sec [Ref 3]. Waves are generated in the intervals of 10 to 60 seconds [Ref 4]. The whole renal pelvis acts as a pacemaker to generate all or none propulsion of urine [Ref 3]. When the frequency of peristaltic contraction reaches that of the pacemaker, the UPJ assumes the form of an open duct [Ref 3] and bolus of urine travels through the ureter at a velocity ranging between 2 to 6 cm/sec [Ref 5]. The following diagram is a simplified representation of the renal pacemaker, calculating the conduction velocity of urine bolus through the ureter's lumen, based on above assumptions.

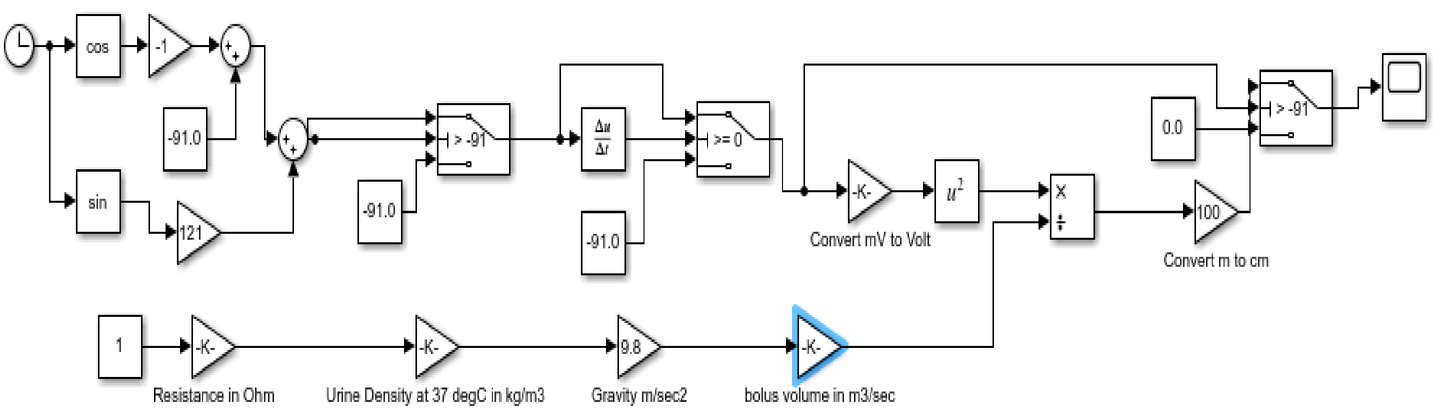

Diagram 1: Simplified representation of the pacemaker acting as an Electro-mechanical pump.

According to The Foundation for Research on Information Technologies in Society (IT'IS) database [Ref 7]., the ureter electric conductivity could be estimated as 0.462 S/m. Assuming that the ureter has a diameter of 5.85 mm [Ref 2], the lump resistance at UPJ could be estimated to be 370 Ω. The combination of renal cortex and the renal medulla cold be estimated to be 1132 Ω. Assuming that a normal human being consumes 2 litters of water in 24 hours, the mean value of a bolus of urine per kidney could be estimated to be 1.16 $x10^{-8}$ [m^3/sec]. The density of urine at 37°C is estimated to be 1.05 [g/cm^3] [Ref 6].

Results

The model above which represents a simplified version of the renal pacemaker was simulated using Matlab Simulink.

Figure 1 shows the synthetic action potential signal. This signal starts at -91 mV and reaches +30mV in 1.5 sec with a refractory period of 5 seconds. There is a 50% difference between the simulated synthetic signal and the data obtained from experimentation.

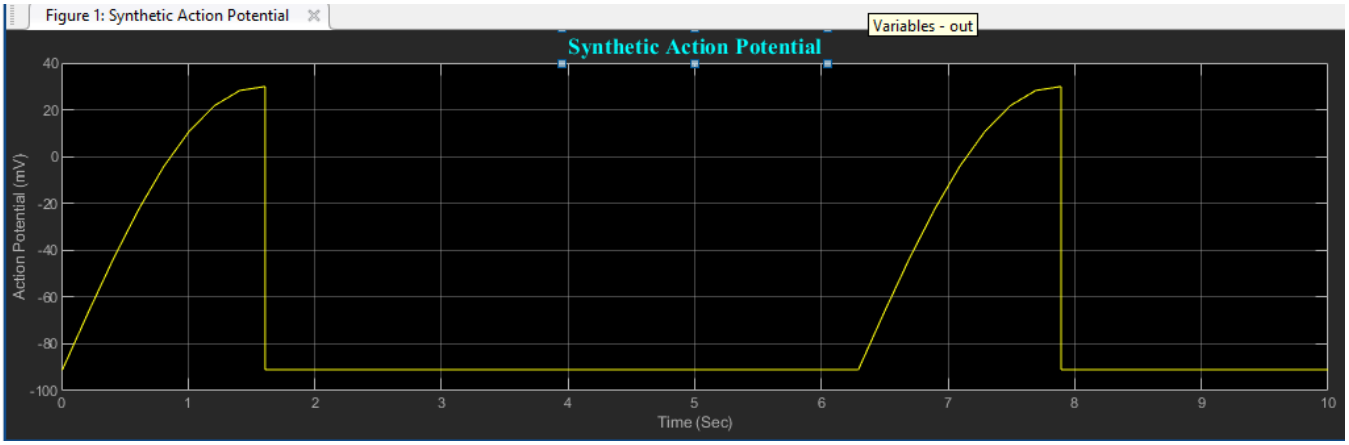

Figure 1: Synthetic Action Potential

Figure 2 shows the simulated conduction velocity of a urine bolus travelling through the ureter's lumen. The simulated value is calculated to be +4.8 cm/sec which is quite in within the tolerance from experimental data.

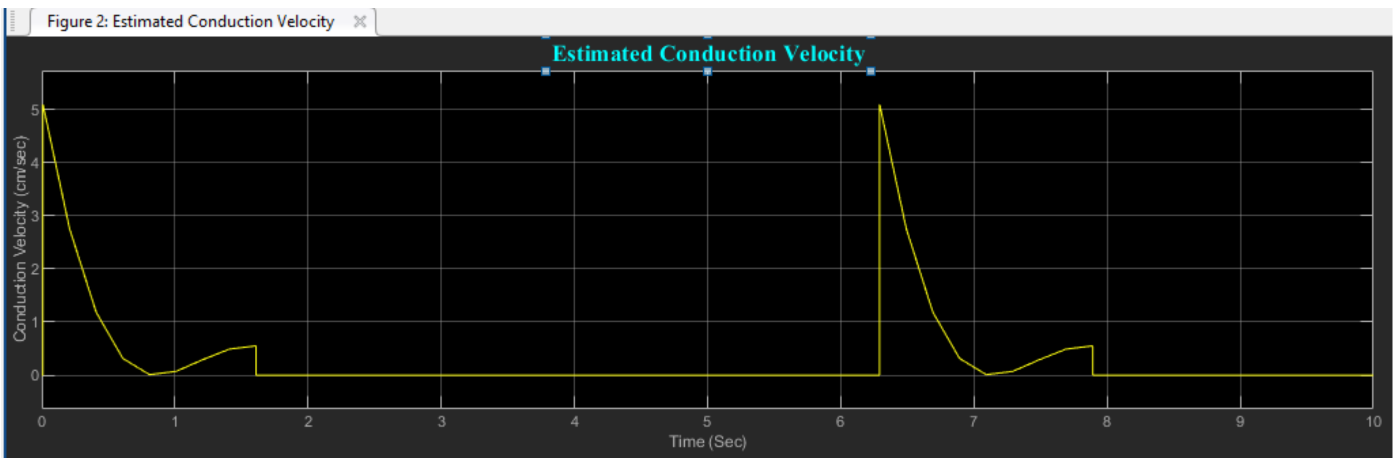

Figure 2: Estimated Conduction Velocity

Conclusion

Human kidney is a vital organ with complex characteristics. Studying its physiology using experimentation could be proven difficult and costly. Mathematical modelling and computer simulation, in conjunction with reasonable and rational assumptions, are tools that could be used in order to describe and study human kidney physiology with acceptable accuracy and minimal cost. The present study has used simple mathematical modelling and computer simulation in order to compute the conduction velocity of urine transport through the ureter in a healthy human being. The kidney was represented as a homogenous medium with a constant temperature, density and conductivity. The complex electro-physiology of the kidney responsible for the pperistalsis was represented by an electro-mechanical pump placed at the junction between the kidney and ureter. The simulation results showed consistency with respect to experimental data.

It could be assumed that portraying complex physiological systems using mathematical modelling, based upon rational assumptions, could be exploited in order to investigate human physiology under traumatic conditions, that would be logistically impossible to perform experimentally.

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