

A Model for Prostate Cryoablation

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1. Introduction

One area of male specific health issues would certainly be disease affecting the prostate. Three main prostatic ailments include, Prostatitis, Benign Prostatic Hyperplasia (BPH), and Cancer. Symptoms of prostatitis include pelvic pain, and pain during urination or ejaculation. Similarly, the enlargement of the prostate induced by BPH, causes a choking off of the urethra, makes urination difficult, and also blocks seminal flow.

Prostate cancer is the most common malignant form of cancer in men in the Western world. Radical prostatectomy has been the treatment of choice in the past; however, complications have resulted in the use of thermal therapies such as microwave, cryotherapy, focused ultrasound, and laser methods.

Cryoablation, a form of cryotherapy, can be used to destroy cancer cells within the prostate. This therapy involves the controlled freezing to cellular kill temperatures of 233 Kelvin (-40°C). The goal is to maintain a sufficiently low intraprostatic temperature that will kill cancerous lesions. Ice nodules that form in the $< 233\text{ K}$ temperature range will effectively kill cancerous cells but an important consideration is the temperature gradient. The leading edge of the nodule will be at about 265 K (-8°C). If a steep temperature gradient could be attained it would allow the edge of the $\ll 265\text{ K}$ hard frozen tissue to virtually reach out to the extremities of the prostate while maintaining a nondestructive temperature at the prostate wall. Unfortunately the frozen tissue obstructs the propagation of sound waves and ultra sound imaging only provides real time data related to the anterior edge of the nodule [1]. It is this last concern that necessitates temperature profile modeling to provide a clear picture of the process of freeze/thaw cycles. Predictive modeling can improve 'kill' success by suggesting proper initial placement and quantity of probes for individual patients.

2. Purpose

The goal of this particular project is to model the time rate freeze development within the prostate, and to provide a fast efficient and user-friendly modeling method. Entries of basic prostate dimensions, and probe location(s) will allow individualized treatment and maximize temperature gradient at diseased tissue, or prostate extremities. Starting with only one cryoablation probe, the transient cooling rate is explored and then additional probes are added in an attempt to maximize the nodule temperature gradient.

3. Modeling

- Prostate is isotropic and homogenous, and perfusion has minimal and decreasing effect during the process.
- At 20 mm outside the boundary of the prostate, the temperature is fixed at 310 K (37°C).
- Temperature of urethra maintained minimally at 310 K.
- Cryoprobe tip approximately 2.3 mm sphere, tip temperature = 80 K (-193°C) with no probe body losses.

A CIRS Model 066 Phantom Prostate is used as the physical model in this project. Basic dimensions: 4.5 cm wide x 5 cm long x 4 cm high. Theoretical modeling will concentrate on maintaining maximum cooling rate in the side view. A 2D slice of the prostate is modeled across the narrowest portion of the prostate and parallel to the urethra.

4. Finite Difference Method

Forward Difference Approximation

Basic theoretical modeling and charting are solved using an excel spreadsheet. The modeling equations are based on the Pennes bioheat equation [2]. To obtain the physical equations Finite Difference discretization was applied to the prostate heat transfer parameters shown in Table 1.

Table: 1
Prostate Physical and Thermal Parameters

Condition	Thermal Conductivity k W/m*K	Density ρ kg/m ³	Specific Heat c J/kg*K	α α = k/ρc
Unfrozen	0.45	1086	3520	1.177E-7
Frozen	2.00	1034	1840	1.051E-6
Slush	1.22	1060	2680	4.295E-7

Heat Equation:

$$\partial/\partial x(k \partial T/\partial x) + \partial/\partial y(k \partial T/\partial y) + \partial/\partial z(k \partial T/\partial z) + q = \rho c_p(\partial T/\partial t)$$

Please note spreadsheet tests condition and then applies correct parameter:

1. α changes depending on the prostate frozen/unfrozen status.
2. Delta t (Δt) is user selected, Δx is calculated, and 2D space is modeled where Δx = Δy.
3. Fo is dependent on the above and Δx is calculated with Fo maximum at 0.24.
4. Steps in 2D space represented by: m and n. Time steps represented by: P.

$$\alpha = k/\rho C \quad (1/\alpha)(\partial T/\partial t) = (\partial^2 T/\partial x^2) + (\partial^2 T/\partial y^2)$$

Fo = αΔt / Δx², and for stability Fo < ¼

$$T^{P+1}_{m,n} = Fo(T^P_{m+1,n} + T^P_{m-1,n} + T^P_{m,n+1} + T^P_{m,n-1}) + (1 - 4Fo)T^P_{m,n}$$

Each cell selects and then applies the appropriate values of k, ρ, and c_p, based on a temperature cut off of 0°C.

5. Results

The two graphs included show temperature versus both time and position relative to the probe. Figure 1 illustrates the tissue temperature at fixed intervals distant from the probe tip. Each individual trace indicates a temperature, ‘sphere of influence’, at a specific time post probe activation. Figure 2 more clearly represents the temperature gradient rate at fixed distance intervals. Several additional charts are needed including multiple probes and probe positions to effectively predict both the temperature gradient and the tissue transient temperatures. The spreadsheet application however, makes it very easy to change and manipulate probe(s) position and duration parameters. Charted results update automatically and instantaneously, allowing a user to tailor results to unique and specific patient conditions.

6. References

[1] Jankun, Monika and Kelly T.J. and Aaim, Amjad and Young, Karen and Keck, Rick W. and Selman, Steven H. and Jankun, Jerzy. *Computer Model for Cryosurgery of the Prostate*. Computer Aided Surgery 1999; Vol 4. No. 4: 193-199.
 [2] Pennes, H.H. Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm. J Appl Physiol 1998; 85: 5-34.

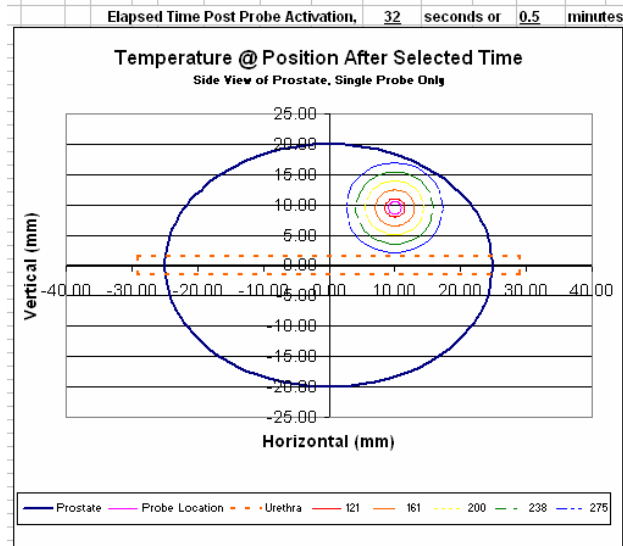


Figure 1

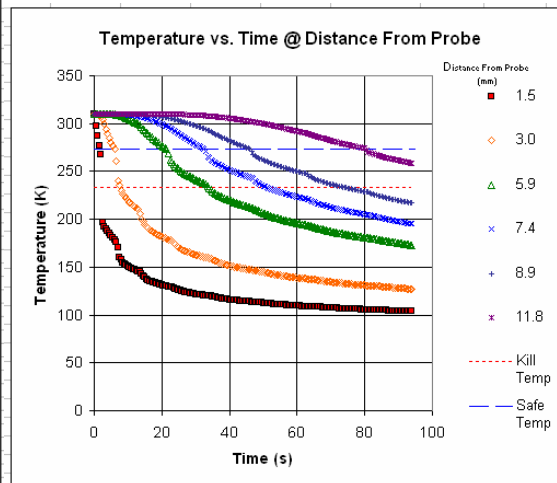


Figure 2