Testicular Thermal Damage and Infertility from Laptop Use

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Executive Summary

Today, more laptop computers are being used on a daily basis than ever before. One of the health risks associated with extended, repeated use by men is that of testicular damage, or reduced spermatogenesis due to increased temperatures in the groin region. Naturally, the scrotum is maintained 2^oC below standard body temperature. However, the combination of increased temperature due to leg positioning to support a laptop on the thighs, and the potential for temperatures of 60^oC to be reached on the bottom, outer surface of the device [11] present a health risk. Although temperatures of 50^oC are more common, they still contribute to a rise of approximately 0.6^oC in addition to a 2.1^oC increase which is already due to leg positioning alone. The direct contact between the thigh and testicles is a significant factor in this increase in temperature, as well as the laptop heat generation. In the future, potential methods of reducing heat conduction into the body may be mitigated by additional heat sinks, or fans which may reduce the effects of extended periods of laptop use.

Introduction: Background and Importance

Infertility (defined as the inability to conceive after 12 months of unprotected intercourse) is estimated to affect 15-20% percent of all couples. Nearly 50 percent of these cases are attributed to male impotency [1]. There is an increased focus on researching factors that could be responsible for male reproductive organ malfunction, including low sperm production. Aside from the influence of genetic factors and diseases, elevated temperatures of the testicles can adversely affect spermatogenesis, and therefore lower sperm count [2]. Proper functioning of the testicles requires the temperature of the scrotum to be maintained at 2–4°C below body temperature, i.e. $32\text{-}34^oC$ [3].

Diseases such as febrile illnesses and retractable testes as well as some simple behaviors (such as wearing tight briefs, taking hot baths or working in environments with constant exposure to high temperatures) play a significant role in whole body or local scrotal heating. One such behavior that is of increasing occurrence is the operation of laptop computers with the computer itself resting on the thighs of the user. Such computers are known to generate heat with internal operating temperatures reaching beyond 70°C [4]. Both the thigh-device contact and the seating posture engaged during the operation of these devices have been demonstrated to increase scrotal temperatures. Though single exposure is not considered significant, repeated conditions of testicular hyperthermia have been shown to permanently hinder sperm production [4]. The increasing frequency of this behavior calls for further research into the possible adverse health consequences. In order to quantify this problem, this report will model the change in scrotal temperature due to heat generation from laptop computers while placed on the thighs.

Design Objectives

In this study we aim to analyze the possibility of damage to sperm production and thus, male fertility, as a direct result of testicular exposure to hyperthermal conditions. Testicular function is temperature dependent and requires a temperature 2-4C below body temperature. Using average physical properties of the male reproductive system external organs[8] as well as average temperature increases resulting from laptop heat generation [10] we will determine the temperature profiles in testicular tissue as a function of time. Since spermatogenesis occurs in the seminiferous tubules throughout the majority of the testes, and can be hindered by a temperature increase of as little as 1°C [9], sperm viability will be affected by increased temperatures at any region in the testes. Temperature increases and associated depths resulting from the seated posture alone, heat generation by correctly-functioning laptops, in which cooling fans and heat sinks maintain a relatively cooler device temperature, laptops with ineffective or malfunctioning cooling systems, and a laptop-cooling pad combination will be analyzed.

Problem Schematic

The operation of a laptop while resting on the thighs (Figure 1) increases scrotal temperatures in multiple ways. Conduction through the tissue, thighs and penis as well as through the air layer trapped between the thighs causes substantial temperature increase; energy is also transferred through radiation. Additionally, heat loss also occurs due to convection in the blood stream that vascularizes the testes.

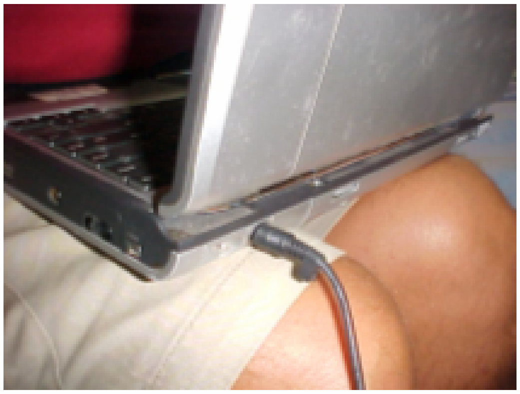

Figure 1. Problem schematic; seated male with a laptop resting on the thighs. Image source: www.bohotraveler.com

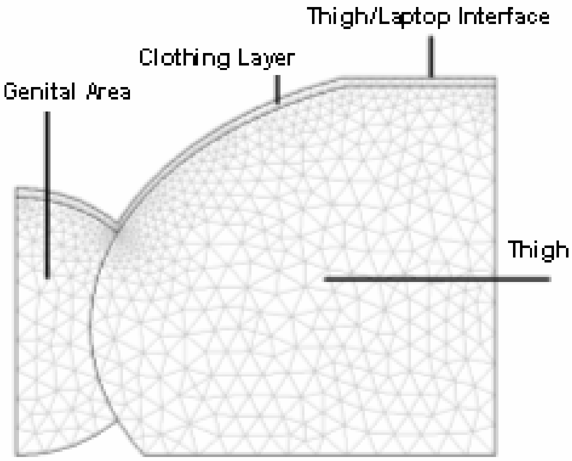

Figure 2. Implemented schematic; cross-section of the groin region right of the axis of symmetry: genitals and upper proximal thigh region

Geometry

Initially taking a cross-section of the thigh/genital region of a seated male with a laptop on his thighs presented geometry too complex to model efficiently. To simplify the problem, while maintaining appropriate analysis parameters, we modeled the region right of the axis of symmetry, which includes the right thigh, testicle, and half of the penis (Figure 2). As we are using the same physical properties for all of the soft tissues, we combined the areas of the (half) penis and testicle adjacent to the thigh to generate our mesh, and only took into consideration tissue depth through the thigh as far as the bottom boundary of the testicle. Additionally, we decreased the thigh area studied to be only that region closest to the genitals, eliminating half of the thigh width. For the clothing, we combined the thickness of underwear and pants to produce one layer, and used averaged physical properties for cotton and wool.

After several trials, our model was chosen because it most accurately depicts the dynamics of this system. This model takes into account heat conduction through the thigh from direct contact, thermal convection on the side of the thigh and testicles, as well as two way radiation of temperature difference between the laptop and tissue. For simplification, the emissivity has been approximated at one. In addition, blood flow has been taken into account with the bio-heat equation which acts as a moderating term, by taking heat away through the blood and bringing tissue temperatures closer to body temperature.

Results and Discussion

Initial temperatures in the model begin at 34.8°C in the testicles, and 37°C in the thigh. After running a simulation of body heat conduction with no laptop, the average genital area temperatures equilibrated to 37.6°C after 4hrs. With the addition of the laptop operating at 53.9°C, the final genital temperature reached 38.0°C. The temperature increase attributed to the laptop is 0.42°C. This result is similar to that found in literature [4], which is 0.6°C. This study also found the average genital temperature increase due to the confinement of the seated posture is 2.1°C and, with the addition of a laptop, a total combined rise of 2.7°C. Under these conditions, our model returns values of 2.8°C, and 3.2°C respectively.

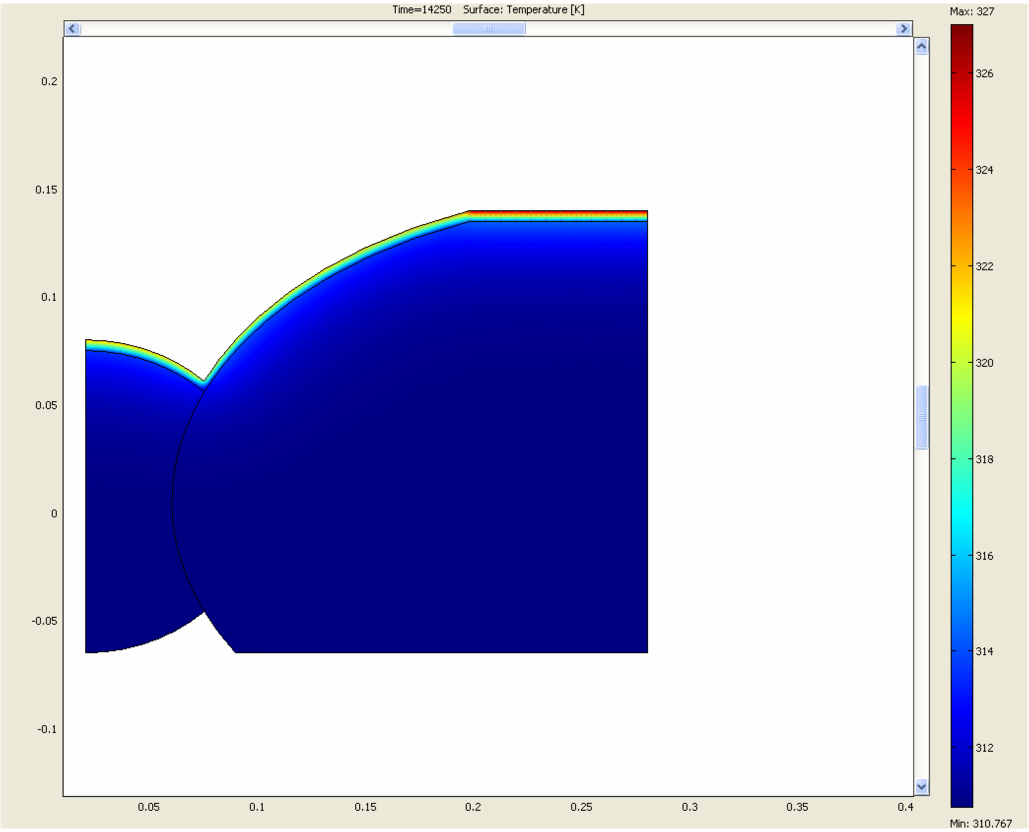

Figure 3. Temperature contour following 4 hours of use of a normal functioning laptop

A contour of the final temperatures in the thigh and genital regions after 4 hours of exposure is shown in Figure 3. As is evident in the image, the greatest temperature changes occurred close to the upper surface, near the laptop location. This was expected, as this region was affected by not only metabolic heat generation, but by the additional convection in the hot air pocket between the laptop and body and conduction from the laptop. Furthermore, when comparing the genital and thigh boundary, higher temperatures are seen in the thigh due to the direct conductive contact with the laptop. Because all other inherent properties which effect temperatures in the region are held constant, we can isolate conductive effects in the upper thigh, and conclude that conduction has a greater effect on local temperature than convection in this scenario.

However, conduction from the laptop had little role in heating the genital region. As a result of placement, and general proximity to the heat source, genital temperature increase is attributed only to blood flow, metabolic heat generation and conduction through the thigh.

The effective heat transfer coefficient is relatively small as a product of low air velocities and therefore, convective heat transfer was minimal. Figure 3 also shows that the body tissues are within a small range of relatively homogenous temperature distributions. This was expected because all tissue properties of the thigh and genital region, were assumed to be isotropic. The similarity, and continuity of temperature change in all regions is an implicative result of the previously referenced homogeneity.

Average genital temperatures for the four different models are summarized in Figure 4 as a function of time. All four scenarios begin to reach a steady state plateau at approximately 9000s (2.5hr) after which temperature increase is small. As can be seen in the diagram, different laptop temperatures as well as the addition of a cooling pad show marked variation in final temperature. The extreme laptop and the addition of a cooling pad to the normal laptop resulted in final average genital temperatures of 38.2^{o}C and 37.9^{o}C, respectively. The cooling pad therefore reduced the steady state temperature of the genitals by 0.7^{o}C relative to the use of a laptop without the cooling pad. This reduced heating was a combination of reductions in convective and conductive heating. However, the difference between the worst case scenario of an overheating laptop and the best case scenario of a normal laptop with cooling pad show minimal difference.

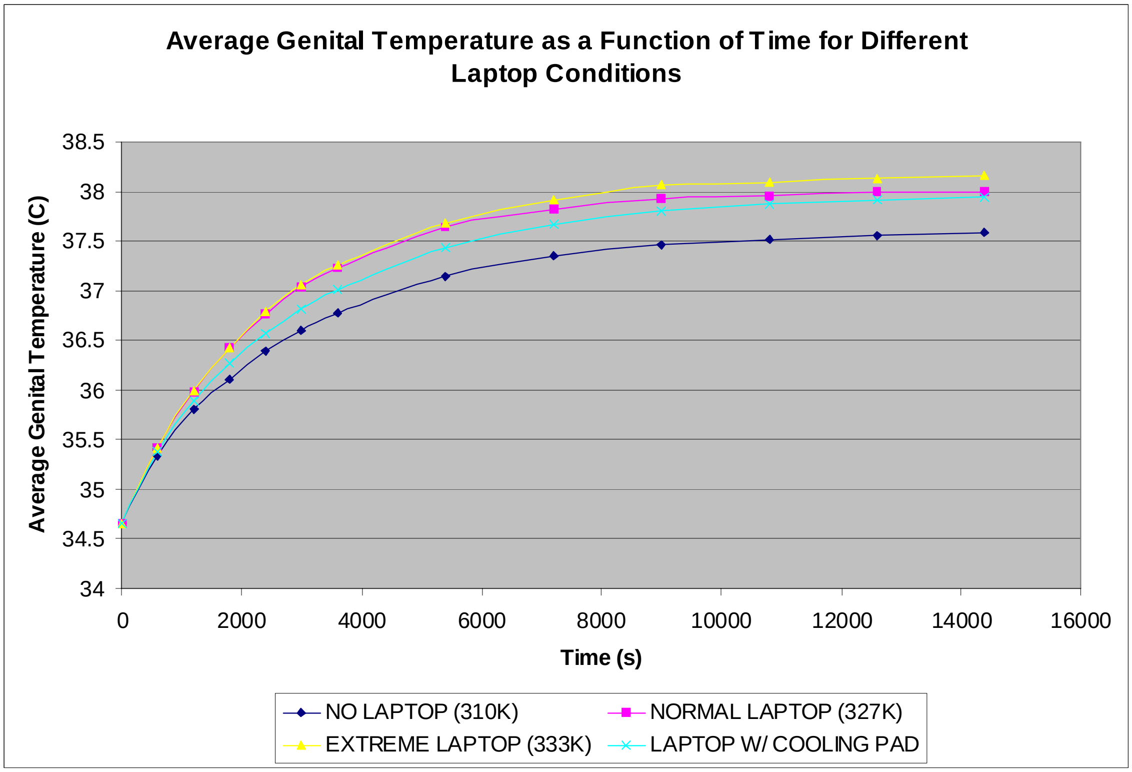

Figure 4. Average genital temperatures over a 4 hour period of sustained sitting without a laptop (dark blue) or with the device placed on the thighs and operating normally (pink), in an overheated state (yellow), or with the aid of a laptop cooling pad (aqua).

Sensitivity Analysis

Due to the nature of the bioheat equation (Appendix A, Equation 1), sensitivity analysis only needed to consider five variations. Variation of any of the blood flow parameters [6] – density, specific heat or volumetric flow rate had only one result as all three of these parameters are multiplied together in the equation. Likewise, variation of the density or specific heat of the tissue had only one result and hence these properties were grouped together for the purpose of sensitivity analysis. A factor of 20% was chosen for the analysis – varied parameters were inputted into the model as 120% and then 80% of the chosen value. The average temperature for the genital region was used as the result for comparison. The time period considered was 4 hours, the same as that of our model. Complete tabulation of results appears in Table 1, with graphical presentation in Figure 5.

Table 2. Sensitivity analysis results. The influence of blood flow, metabolic heat generation, tissue properties, convective heat transfer coefficient, and thermal conductivity were studied under a simulation time of 4 hours.

	Parameter Varied		Genital Temperature (°C)	Difference from Model (°C)
Effect of Blood Flow	**V_b (m^3 blood/ m^3 tissue(s), c_p (J/kg), or ρ (kg/m^3)**	120% V_b=4.38e-4	37.825	-0.173
		80%V_b =2.92e -4	38.240	0.242
Generation Effect of Metabolic Heat, Q (W/m^2)	**Q (W/m^2)**	120% Q=1320	38.152	0.153
		80% Q= 880	37.845	-0.154
Effect of Tissue Properties	**c_p (J/kg), or ρ (kg/m^3)**	120% c_p = 4260	37.970	-0.029
		80% c_p = 2840	38.017	0.018
Effect of Convective Heat Transfer Coefficient	**h_{air} (W/m^2 •K)**	120% h_{air} = 5.604	38.008	0.009
		80% h_{air} = 3.736	37.988	-0.010
Effect of Thermal Conductivity	**K (W/m•K)**	120% k = 0.504	38.002	-0.008
		80% k = 0.336	37.994	0.014

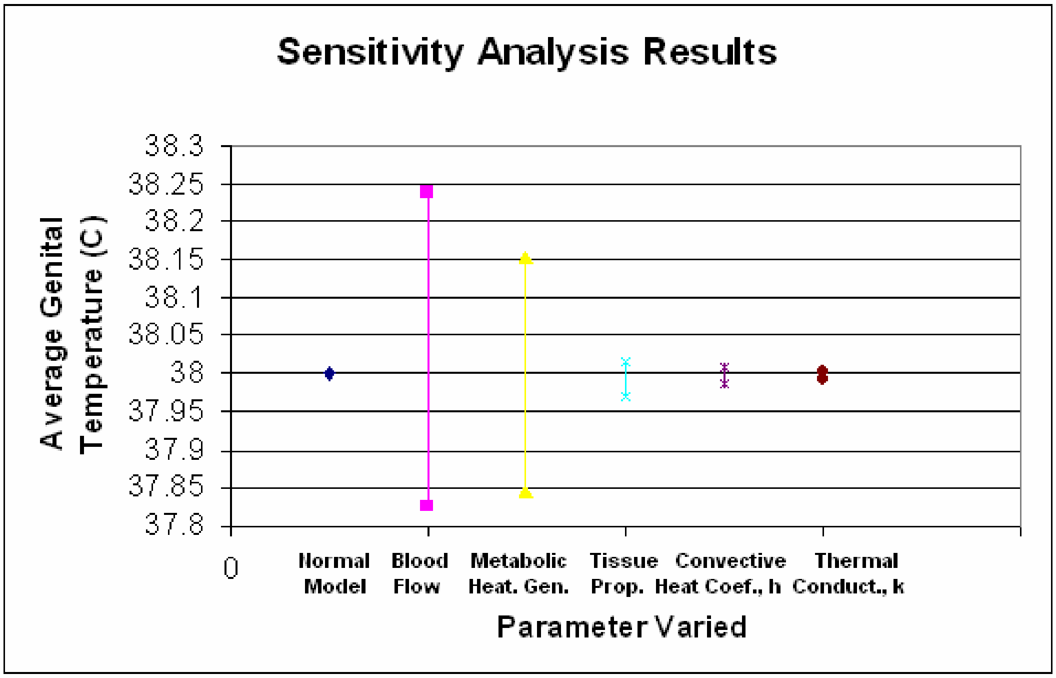

Figure 5. Graphical representation of sensitivity analysis, in which input properties were varied by +/- 20%. The model is most sensitive to variations in blood flow and metabolic heat generation.

The model was found to be most sensitive to the blood flow and metabolic heat generation. Variation of these parameters during sensitivity analysis resulted in at least 5 times the increase or decrease in genital temperature exhibited by the other parameters. These are therefore the two parameters that govern the behavior of the model. Although it seems odd that the model behavior is not heavily dependent on the laptop temperature, these results are actually in accordance with what should be expected. According to the results of our earlier literature search, prolonged sitting for males is alone a high risk activity [4]. Without the additional heat from a laptop, the genitals are still brought to equilibrium with the rest of the body, a temperature that is inhibitory to spermatogenesis. This is a result of blood flow between the warmer body tissues and the cooler genital tissues as well as the constant heat generated by metabolic activity. It therefore is logical that the blood flow will still play a large role in the genital temperature increase as temperature equilibration is one of the blood's important roles.

It is also important to note that there remains a degree of uncertainty in our choice of blood flow parameters and metabolic heat generation due to a lack of literature and research into the true value of these parameters. Additionally, natural variation of these parameters with age and build of the user be must be considered for an improved level of accuracy. Considering the high sensitivity of the model to these input values, further investigation is required.

Conclusion:

Before modeling this problem in COMSOL, our original hypothesis was that there would be a greater temperature change with the presence of an external heat source. However, the model indicates that although the laptop does contribute a modest increase in temperature, the largest portion of this was due to bodily conduction of warmer temperatures from the thigh, to the genital area. Additionally, metabolic heat generation played a role, but quite possibly the most important factor, was the lack of free flowing air which would typically keep this region at its optimal, sub-body temperature in different posture settings. While these effects were surprising at first, rational explanations and clinical trials showed that the modeled results were concurrent with actuality [4].

The simulation also showed drastic (5^{o}C) internal variations between the top and bottom of the genital region. This was in part due to the fact that the top of this region was in direct proximity to the heat source, while the bottom was shielded.

Several other major findings came as the result of our study. We found that with heating from a laptop, little change occurs in the region after 2.5 hours. Although no appreciable further temperature increases occur after this point, it is still likely that continued thermal damage to spermatogenesis persists throughout lengthened periods of use. It is difficult to estimate specifics of damage throughout this time period, because of the inherent sensitivity of the region, and lack of adequate data to suggest the consequences of such conditions. Further research into the effects of these steady state temperatures on spermatogenesis is required, as well as those of repeated exposure.

It is important also to note that the many other daily activities can have the same effect of increasing genital temperature. Hot showers and heavy exercise for example also cause genital temperatures to rise and are relatively unavoidable. It is sensible then to regard temperature rise as a result of laptop use an acceptable risk occasionally. Only from prolonged, perpetual use does excess heating become a considerable risk [3].

On a similar note, our model of a commercial rubber cooling pad [10] did reduce the observed increase in scrotal temperature. Over a 4 hour period, the cooling pad contributed to an overall average decrease of 0.1^{o}C. Despite a seemingly small change, this represents a 17% decrease in temperatures when taking solely the laptop into consideration. As a result however, there is still 0.4^{o}C greater scrotal temperature in this case than with no laptop use at all. Therefore, although the cooling pad is a helpful addition, it does not fully negate the heating effects of the laptop and seated position.

We were unable to take into account some factors which may have potentially played a role in the model. Thigh and testicular dimensions are difficult to approximate due to their variability in different sitting positions [8]. Also, conductive cooling on the bottom of the genital region and effects of variations in clothing were negated for simplicity. The effects of other cooling pads on the market, some of which include airflow from internal fans were not modeled, but it is plausible that some of these possibilities would offer further reduction of associated laptop temperatures.

Despite these assumptions, concrete data from physical experiments[9] confirmed our model nonetheless. The relative similarity between results previously cited and those our model yielded is a good indication that our model is an accurate representation of the thermal behavior seen with the combined effects of the body, and laptop. Even so, closer agreement is necessary in order to yield definitive physiologic results, due to the sensitivity of the testicles to a fine range of temperatures. Noting this, we can conclude that the majority of temperature rise is due to factors other than the laptop: unavoidable, posture induced confinement resulting in conduction from the thighs. However, given the natural variability of the input parameters and the high sensitivity of the region to temperature change, further research and modeling is required for a more accurate study. Although this model shows the contribution from a laptop to be proportionally small, this change is significant enough to encourage further studies and to also concern frequent laptop users, especially those who plan to conceive

Design Recommendations

There are many areas for improvement in our model. Although all input values were found in scientific writings, the ranges for each of these parameters are large and therefore need further investigation. Metabolic heat generation, specific heats and density for both blood and tissue and the thermal conductivity of the tissue should be researched. The metabolic heat generation and properties of the blood are especially important here as our sensitivity analysis found them to have the largest effect on the model. There seems to be a lack of literature on these topics specific to the thigh and genitals and it is likely that clinical experimentation will need to be conducted. Additionally, the heat transfer coefficient used in our model was found using natural convection over a cylinder, yet still fell in an acceptable range [12]. This is another property that should be further explored as the thighs are not perfect cylinders and become distorted in the seated position.

It should also be noted that the geometry we employed cannot be reflective of every consumer. Simple geometry assessments could be conducted on a group of males to get an average and more inclusive geometry. Our geometry was chosen specifically to the average male college student and is therefore only reflective of a portion of the market. A 3D model should also be explored that would include the effects of the fans and the small amount of bulk flow that these could induce. Such a model would incorporate the laptop as more than a slab of higher temperature and would provide a less general solution.

Another area of the model that could be changed to increase the accuracy is the number of regions and tissues that were considered. In order to minimize the computing power needed by our model and to keep the geometry simple, clothing was reduced to one homogenous layer, as was thigh tissue and genital tissue. In some cases, the latter two were even considered isotropic in regards to density, thermal conductivity and blood flow used. By adding the layers of the skin, adipose tissue, muscle, and highly-vascularized penis [5] with their specific properties, model accuracy could be improved. Also, a more specific region for spermatogenesis is required. Scientific documentation of this is rare, especially taking displacement from sitting into account (we were unable to find any references), and therefore research and tests are required. This would allow the results and implications of the model to be interpreted with better accuracy – instead of considering average genital temperature, the temperature at spermatogenic regions could be found.

Finally, the temperature dependence of blood flow and metabolic heat generation could be included. Under hyperthermic conditions, we can expect the metabolic heat generation to decrease and the blood flow to increase. Both of these mechanisms would reduce the extent of temperature increase and are therefore important considerations.

Constraints and Implications of the Model

Due to the nature of the project – our model is intended to provide insight into a problem rather than as a design to alleviate a problem; our model has implications rather than constraints. Our model affirms that the operation of computers resting on the lap could affect spermatogenesis and increase risk of male infertility. The implications of this are huge. Laptop manufacturers could face legal action in the future and be forced to re-evaluate their product design. Upon publication of these findings, consumers will likely expect laptop manufacturers to assume an ethical responsibility. Additional heat sinks and fans will need to be added to the computers and improved cooling devices designed. The cooling device that we modeled showed minimal reduction of hyperthermia. This will have a two fold impact – firstly, consumers will respond with demands of improvement and secondly, more laptop users will purchase the cooling devices when they are shown to be beneficial. Design specifications will need to be adjusted to make these devices more efficient and thorough testing and proof of the benefits of these devices will be required. This will definitely affect the laptop manufacturers – both new designs and new manufacturing lines will be needed. Manufacturability could be adversely affected by these changes. Furthermore, it can be expected that laptop users will respond on an individual basis out of concerns for their health and safety and reduce their on-lap use.

Appendices

Appendix A: Mathematical Statement of the Problem

Governing Equations:

Bioheat conduction equation: $\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + \rho_b c_b V_b^v (\dot{T}_a - T) + \mathrm{Q}$ (Equation 1)

Boundary Conditions:

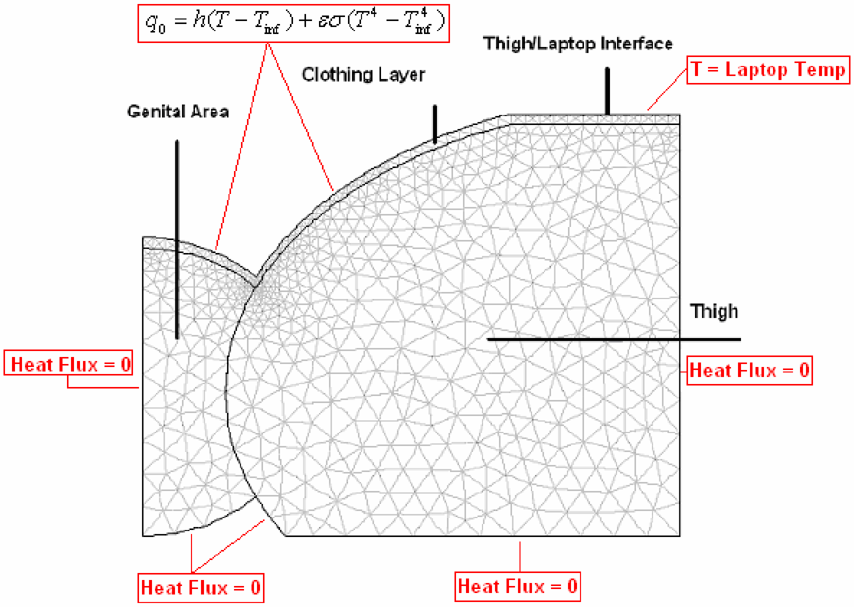

Figure 6. Mesh with boundary conditions. Zero heat flux through the axis of symmetry of the genital region, the insulation at the bottom curved genital and thigh surfaces (clothing and seat), or the semi-infinite bottom and right thigh boundaries. Heat flux across the top curved surfaces of the genitals and thigh are equal to convective and radiative heat transfer. The thigh/laptop interface is set to a temperature appropriate for each of the conditions modeled.

Initial Conditions:

Layer	InitialTemp(K)
Clothing, thigh	309
Clothing, groin	308
Thigh	310
Penis/Testicle	307.8
Blood	310
Air	310
Laptop	327

Appendix B:

Solver used:

Linear System Solver Direct (UMFPACK)
Transient Analysis with Auto Select Solver

Time Stepping:

Automatic Time Stepping
Times to store in output set to 200s = 3minutes and 20 seconds
Time Steps taken by solver: Free

Tolerance:

Relative Tolerance: 0.01
Absolute Tolerance: 0.0010

Element Mesh:

Default Element Type: Lagrange – Quadratic
Type of Mesh: Predefined Mesh – normal, Optimize Quality, Refinement Method Regular

COMSOL Model Report

2. Model Properties

Property	Value
Model name	
Author	
Company	
Department	
Reference	
URL	
Saved date	Apr 29, 2007 1:14:03 PM
Creation date	Feb 27, 2007 7:11:08 PM
COMSOL version	COMSOL 3.3.0.405

File name: C:\Documents and Settings\aben453\Desktop\ses77\Laptop Infertility.mph
Application modes and modules used in this model:
Geom1 (2D)
Convection and Conduction

3. Constants

Name	Expression	Value	Description
rho_b	1000		Blood Density (kg/m3)
c_b	3780		Blood Specific Heat Capacity (J/kgK)
V_b	3.65e-4		Blood Flow Rate (m3 blood/m3 tissue-sec)),thigh, genitals
T_a	310		Arterial Blood Temperature (K)
Hair	4.67		H over the thigh and genital regions (W/m2K)
Tinf	298		Air Temperature - assumed as Room temp, removed laptop
sigma	5.67E-8		Stefan-Boltzmann's constant for radiation

Tlap	327		Laptop Temperature (in K)
Qgen	1100		Metabolic Heat Gen units(W/m^3)

4. Geometry

Number of geometries: 1

5. Geom1

Space dimensions: 2D

Independent variables: x, y, z

5.1. Mesh

5.1.1. Mesh Statistics

Number of degrees of freedom	2689
Number of mesh points	697
Number of elements	1296
Triangular	1296
Quadrilateral	0
Number of boundary elements	163
Number of vertex elements	15
Minimum element quality	0.696
Element area ratio	0.003

5.2. Application Mode: Convection and Conduction (cc)

Application mode type: Convection and Conduction

Application mode name: cc

5.2.1. Application Mode Properties

Property	**Value**
Default element type	Lagrange - Quadratic
Analysis type	Transient
Equation form	Non-conservative
Frame	Frame (ref)
Weak constraints	Off

5.2.2. Variables

Dependent variables: T

Shape functions: shlag(2,'T')

Interior boundaries not active

5.2.3. Boundary Settings

Boundary		1-3, 6-7, 14	5
Type		Thermal insulation	Temperature
Inward heat flux (q0)	W/m^2	0	0
Temperature (T0)	K	0	**327**

Boundary	8	10, 16
Type	Thermal insulation	Heat flux

Inward heat flux (q0)	**hairs*(Tlap-T)+sigma*(Tlap^4-T^4)**	**hair*(Tlap-T)+sigma*(Tlap^4-T^4)**
Temperature (T0)	0	0

5.2.4. Subdomain Settings

Subdomain		1	2
Thermal conductivity (k)	W/(m·K)	**.420**	**0.035**
Density (rho)	kg/m^3	**1044**	**1480**
Heat capacity (C)	J/(kg·K)	**3550**	**1298**
Heat source (Q)	W/m^3	**rho_b*c_b*V_b*(T_a-T)+Qgen**	0

Subdomain	3
Thermal conductivity (k)	**.420**
Density (rho)	**1044**
Heat capacity (C)	**3550**
Heat source (Q)	**rho_b*c_b*V_b*(T_a-T)+Qgen**

Subdomain initial value		1	2	3
Temperature (T)	K	307.8	308	310

6. Solver Settings

Solve using a script: off

Analysis type	Transient
Auto select solver	On
Solver	Time dependent
Solution form	Automatic
Symmetric	Auto
Adaption	Off

6.1. Direct (UMFPACK)

Solver type: Linear system solver

Parameter	**Value**
Pivot threshold	0.1
Memory allocation factor	0.7

6.2. Time Stepping

Parameter	**Value**
Times	0:200:14400
Relative tolerance	0.01
Absolute tolerance	0.0010
Times to store in output	Specified times
Time steps taken by solver	Free

Manual tuning of step size	Off
Initial time step	0.0010
Maximum time step	1.0
Maximum BDF order	5
Singular mass matrix	Maybe
Consistent initialization of DAE systems	Backward Euler
Error estimation strategy	Include algebraic
Allow complex numbers	Off

6.3. Advanced

Parameter	**Value**
Constraint handling method	Elimination
Null-space function	Automatic
Assembly block size	5000
Use Hermitian transpose of constraint matrix and in symmetry detection	Off
Use complex functions with real input	Off
Stop if error due to undefined operation	On
Type of scaling	Automatic
Manual scaling	
Row equilibration	On
Manual control of reassembly	Off
Load constant	On
Constraint constant	On
Mass constant	On
Damping (mass) constant	On
Jacobian constant	On
Constraint Jacobian constant	On

8. Variables

8.1. Boundary

Name	**Description**	**Expression**
ndflux_T_cc	Normal conductive heat flux, T	nx_cc * dflux_T_x_cc+ny_cc * dflux_T_y_cc
ncflux_T_cc	Normal convective heat flux, T	nx_cc * cflux_T_x_cc+ny_cc * cflux_T_y_cc
ntflux_T_cc	Normal total heat flux, T	nx_cc * tflux_T_x_cc+ny_cc * tflux_T_y_cc

8.2. Subdomain

Name	**Description**	**Expression**

Grad_T_x_cc	Temperature gradient, T, x component	Tx
Dflux_T_x_cc	Conductive heat flux, T, x component	-kxx_T_cc * Tx-kxy_T_cc * Ty
Cflux_T_x_cc	Convective heat flux, T, x component	rho_T_cc * C_T_cc * T * u_T_cc
Tflux_T_x_cc	Total heat flux, T, x component	dflux_T_x_cc+cflux_T_x_cc
Grad_T_y_cc	Temperature gradient, T, y component	Ty
Dflux_T_y_cc	Conductive heat flux, T, y component	-kyx_T_cc * Tx-kyy_T_cc * Ty
Cflux_T_y_cc	Convective heat flux, T, y component	rho_T_cc * C_T_cc * T * v_T_cc
Tflux_T_y_cc	Total heat flux, T, y component	dflux_T_y_cc+cflux_T_y_cc
beta_T_x_cc	Convective field, T, x component	rho_T_cc * C_T_cc * u_T_cc
beta_T_y_cc	Convective field, T, y component	rho_T_cc * C_T_cc * v_T_cc
Grad_T_cc	Temperature gradient, T	sqrt(grad_T_x_cc^2+grad_T_y_cc^2)
Dflux_T_cc	Conductive heat flux, T	sqrt(dflux_T_x_cc^2+dflux_T_y_cc^2)
Cflux_T_cc	Convective heat flux, T	sqrt(cflux_T_x_cc^2+cflux_T_y_cc^2)
Tflux_T_cc	Total heat flux, T	sqrt(tflux_T_x_cc^2+tflux_T_y_cc^2)
cellPe_T_cc	Cell Peclet number, T	h * sqrt(beta_T_x_cc^2+beta_T_y_cc^2)/Dm_T_cc
Dm_T_cc	Mean diffusion	(kxx_T_cc * rho_T_cc^2 * C_T_cc^2 * u_T_cc^2+kxy_T_cc * u_T_cc * rho_T_cc^2 * C_T_cc^2

	coefficient, T	* v_T_cc+kyx_T_cc * v_T_cc * rho_T_cc^2 * C_T_cc^2 * u_T_cc+kyy_T_cc * rho_T_cc^2 * C_T_cc^2 * v_T_cc^2)/((rho_T_cc * C_T_cc * u_T_cc)^2+(rho_T_cc * C_T_cc * v_T_cc)^2+eps)
res_T_cc	Equation residual for T	-kxx_T_cc * Txx-kxy_T_cc * Txy+Tx * rho_T_cc * C_T_cc * u_T_cc-kyx_T_cc * Tyx-kyy_T_cc * Tyy+Ty * rho_T_cc * C_T_cc * v_T_cc-Q_T_cc
res_sc_T_cc	Shock capturing residual for T	Tx * rho_T_cc * C_T_cc * u_T_cc+Ty * rho_T_cc * C_T_cc * v_T_cc-Q_T_cc
da_T_cc	Total time scale factor, T	Dts_T_cc * rho_T_cc * C_T_cc

Mesh Convergence

To test the sensitivity of our model to the mesh quality, we evaluated genital temperature after 4 hours of laptop use in comparison to varying degrees of mesh refinement. The results in Table 3 and Figure 7 indicate that even with as broad a range of 1,296 to 20,736 elements, there was no temperature increase on an applicable scale. Therefore, a mesh with 1,296 elements (Figure 2) was used for data analysis without compromising accuracy.

Table 2. Mesh convergence analysis, simulation time of 4 hours

Number of Mesh Elements	**Number of Mesh Points**	**Average Genital Temperature (°C)**
1,296	697	37.23
5,184	2,689	37.23
20,736	10,561	37.23

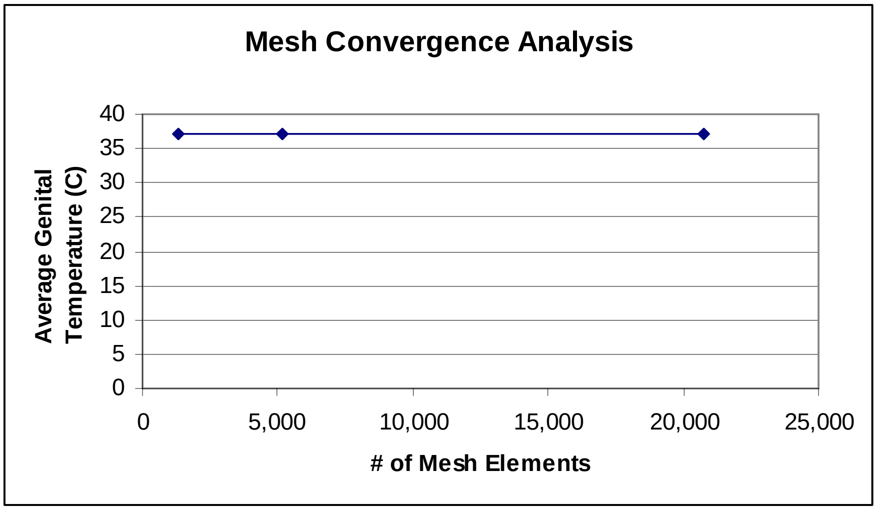

Figure 7. Graphed results of mesh convergence analysis; average genital temperature as a function of number of mesh elements. Simulation time: 4 hours.

Appendix C: Input Parameters

Table 4. Input parameters used for convective heat transfer calculations

Calculating "hair" values to be used in the model, based on natural convection over a cylinder

	Scrotum	Thigh
Tissue Temp (in K)	307.8	310
Air Temp (taken as the laptop temperature, in congruence with the model, K)	327	327
Delta T (K)	19.2	17
Gravity constant(m/s^2)	9.8	9.8
Dynamic Viscosity (mu) (kg/m-sec)	1.95E-05	1.95E-05
Air conductivity (k, W/mK)	0.02853	0.02853
Characteristic Length (d)	0.08	0.24
Rho (density) (kg/m3), air	1.14	1.14
Beta (1/T)	0.003058104	0.003058104
k (w/m-K), tissue	4.20E-01	4.20E-01
Specific Heat of Tissue (J/kg)	3550	3550
Specific Heat of Air (J/kg)	1007	1007
Prandtl Number	**6.88E-01**	**6.88E-01**
(0.559/Pr)^(9/16)	0.889565318	0.889565318
Raleigh Number	**6.93E+05**	**1.66E+07**
RA^1/6	9.407164039	15.96653314
RA^1/3	88.49473525	254.9301804
GR number	**1.01E+06**	**2.41E+07**
Nusseldt Number, cyl	**13.06809227**	**32.68694041**
Nu Number, Flat Horiz	**12.38926293**	**35.69022525**
h (W/m^2-K), Flat, Horiz	**4.418320894**	**6.25E+01**
h (W/m^2-K), cyl	**4.660408406**	**3.885660041**

Note: Even though two separate values were calculated for the tissues, only the thigh heat transfer coefficient was used because in the seated posture, the thigh and genital tissues are in close contact and act almost as a blended material. Furthermore, the difference between the two values is minimal and in assuming only one value, the computing power that was required for the simulation was reduced.

Modeling metabolic heat generation

In modeling Q, literature only provided values for the basal metabolic rate of skeletal muscle [12]. Furthermore, this was a large range of values. In order to find a useful value, the data was first normalized to fit our equations (W/m^2). Of this range we initially chose a value about 80% of the maximum as we were modeling the thigh of a young person with a high metabolism. To verify this choice, the laptop effects were removed from the model and the simulation run for 4 hours. The result was that a huge (5^oC) increase in the thigh temperatures. This indicated that our choice of Q was much too high - body temperature should not undergo such substantial increases as a result of sitting. We then chose smaller values of Q – considering that the person is resting, there was minimal muscular activity, and because the metabolic rate would decrease as a result of local temperature increases. We conducted a number of iterations until we found a reasonable value of $1100W/m^2$ which resulted in an increase of 0.5^oC after 4 hours of sitting. This value still fell in the range given, on the lower end.

Cooling Pad

In the case of many commercial laptop cooling pads, heat conduction coming from the laptop through the user's body is mitigated by means of a rubber, air space mesh with a low thermal conductivity. In a simplified model, we approximated this mesh to be a uniform material with constant properties. This method yields properties of a combined average of observed air space, and rubber material [11]. This average was found using the following approximation: $i_{eff}= f_{open}\ i_{air}+ (1- f_{open})\ i_{rubber}$ where i = effective thermal conductivity (k_{eff}), density (ρ_{eff}), and specific heat ($c_{p(eff)},$) of the cooling pad while f_{open}

is the volumetric ratio of the air spaces and the rubber (mass ratio in the calculation for specific heat capacity). The following tabulated values were determined:

Table 4. Determined values for cooling pad

ρ_{eff} (kg/m^3)	k_{eff} (W/m.K)	$c_{p(eff)}$, (J/kg)
699.8276	0.254	1.354

Appendix D: References:

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