A Heat Dissipation Tutorial for Wearable Computers

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Abstract

Wearable computing brings computation much closer to the user for everyday tasks and may be worn during most of the day. However, with CPU and wireless network intensive applications, higher power microprocessors and radio links are necessary, resulting in increased heat generation. This paper suggests a method to increase the heat dissipation capability per unit surface area of a mobile computer by coupling it to the user. In addition, this paper presents tools and guidelines for determining the placement of heat dissipating components.

1. Heat dissipation for body-centered devices

Demand for higher computational power in notebook computers has forced hardware designers to plan CPU heat dissipation carefully. However, as owners of high-end laptops will testify, the surface of the machine may still get uncomfortably hot. As high end computers are incorporated into smaller form factors, this problem will worsen. Wearable computers would seem to have particular difficulties since the computer housing may be in prolonged contact with skin. However, this paper suggests that wearable computers may provide a better form factor then today's notebooks in regard to heat dissipation.

An obvious approach to the problem of heat generation is to decrease the power required for high-end CPUs through higher integration, optimized instruction sets, and more exotic techniques such as "reversible computation." However, profit margins, user demand, and backwards compatibility concerns are pushing industry leaders to concentrate on processors requiring more than 5W. In addition, the explosion of mobile peripherals, such as wireless Internet radios, video cameras, sound cards, body networks, scanners, and GPS units creates an ever higher heat load as functionality increases. An example of this effect is the U.S. Army's modern (late 1990's) soldier, who is expected to dissipate 30W on communications gear alone! Thus, even with improved technology, heat dissipation will continue to be an issue in the development of mobile devices.

Current systems try to insulate the user from heat sources, slowing or shutting down when internal temperatures get too high. However, the human body is one of the most effective and complex examples of thermoregulation in nature, capable of dissipating over 2700W of heat [5]. Thus, the human body itself might be used to help dissipate heat. However, to take advantage of this system, some background knowledge is necessary. The next section discusses the fundamentals of human heat regulation and thermal comfort. However, for a more thorough discussion see [14, 5].

2. Thermoregulation in humans

In the extremes, the human body generates between 80W to 10,000W of power [12, 13]. With proper preparation, it can survive in the hot Saharan desert or on the ice in Antarctica for extended periods. Yet, the body maintains its "core" temperature (the upper trunk and head regions) at 37^oC, only varying +/- 2^oC while under stress (in medical extremes, +/- 5^oC may be observed) [5]. Obviously, the human body can be an excellent regulator of heat. However, the sedate body is comfortable in a relatively narrow range of environmental temperatures. Even so, the amount of heat that is exchanged in this comfort range can be significant when all the different modes are considered. Heat balance in the human body can be expressed by

$$M' - W' = Q'_{evap} + Q'_{conv} + Q'_{rad} + Q'_{cond} + Q'_{stor}$$

where M' is the rate of heat production (due to metabolism), W' is rate of useful mechanical work, Q'_{evap} is rate of heat loss due to evaporation, Q'_{conv} is the rate of heat gained or lost (exchanged) due to convection, Q'_{rad} is the rate of heat exchanged by radiation, Q'_{cond} is the rate of heat exchanged by conduction, and Q'_{stor} is the rate of heat storage in the body heat. Thus, total body heat may increase or decrease resulting in changes in body temperature [5].

Body heat exchange is very dependent on the thermal environment. The thermal environment is characterized

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by ambient temperature (^oC), dew point temperature (^oC) and ambient vapor pressure ($\frac{kg}{m \cdot sec^2}$), air or fluid velocity ($\frac{m}{s}$), mean radiant temperature (^oC) and effective radiant field($\frac{W}{m^2}$), clothing insulation (clo), barometric pressure ($\frac{kg}{m \cdot sec^2}$), and exposure time. Ambient temperature is simply the temperature of the environment outside of the influence of the body. The dew point temperature is the temperature at which condensation first occurs when an air-water vapor mixture is cooled at a constant pressure. Ambient vapor pressure is also a measure of humidity and, for most cases, is the pressure exerted by the water vapor in the air. Air and fluid movement are the result of free buoyant motion caused by a warm body in cool air, forced ventilation of the environment, or body movement. Mean radiant temperature and the effective radiant field describe radiant heat exchange. Mean radiant temperature (MRT) is the temperature of an imaginary isothermal "black" enclosure in which humans would exchange the same amount of heat by radiation as in the actual nonuniform environment. Effective radiant field (ERF) relates the MRT or the surrounding surface temperatures of an enclosure to the air temperature. The "clo" is a unit of clothing insulation which represents the effective insulation provided by a normal business suit when worn by a resting person in a comfortable indoor environment. It is equivalent to a thermal resistance of $0.1547\frac{m^{2o}C}{W}$ or a conductance of $6.46\frac{W}{m^2 \cdot {}^oC}$. Barometric pressure is caused by the atmosphere and usually expressed in kPa (1000 $\frac{kg}{m \cdot sec^2}$) or torr. While the following sections will address these variables where appropriate, the reader is encouraged to read [8] and [5] for a more extensive treatment.

For most discussions, the outer skin is considered the heat exchange boundary between the body and the thermal environment. Heat exchange terms reflect this, having units of $\frac{W}{m^2}$. A good approximation of an individual's skin surface area is given by the Dubois formula

$$A_D = 0.202m^{0.425}H^{0.725}$$

where A_D is the surface area in square meters, m is body mass in kilograms, and H is height in meters [8]. For convenience, we assume a user with a skin surface area of $1.8m^2$ and a mass of $70kg$.

2.1. Convection

In an environment where air temperature is cooler than that of the skin or clothing surface, the air immediately next to the body surface becomes heated by direct conduction. As the air heats, it becomes less dense and begins to rise. This occurs everywhere about the body and forms a microenvironment where heat is transferred by convection This air flow is called the natural convection boundary layer [5].

Due to the complexity of the problem, mathematical analysis of convection heat loss on the human body have not been developed. However, experimental approximations have been proposed. For natural convection in both seated and standing positions, Fanger [7] presents a convection coefficient h_c of

$$h_c = 2.68(t_{cl} - t_a)^{0.25}$$

in units of $\frac{W}{m^{2o}C}$, where t_{cl} is clothing surface temperature and t_a is the ambient temperature.

Convection also occurs when a breeze is present. For uniform forced air flows under $2.6\frac{m}{s}$, Fanger [7] suggests an approximation of

$$h_c = 12.1\sqrt{V}$$

where V is air velocity. When a slight breeze is present both the natural and forced air convection formulas should be calculated and the larger value used. In his book, Clark [5] also presents an experimental formula of

$$h_c = 8.3\sqrt{V}$$

without providing a constraint on air flow speed. In addition, Clark states that h_c is doubled when the air flow is turbulent based on experimental evidence with appropriately sized and instrumented heated cylinders.

2.2. Radiation

Heat can be exchanged between two bodies by electromagnetic radiation, even through large distances. For the purposes of heat exchange to and from the human body, this paper is concerned with radiation from sources cooler than 100^oC. The Stefan-Boltzmann formula can be used to determine the total emissive power of a wavelength at absolute temperature T

$$W_b = \epsilon\sigma T^4$$

where ϵ is the emittance of the body, and σ is the Stefan-Boltzmann constant ($5.7 \times 10^{-8}\frac{W}{m^2 \cdot {}^oK^4}$). The emittance of an object is the ratio of the actual emission of heat from a surface to that of a perfect black body, equally capable of emitting or absorbing radiation at any wavelength. The emittance for human skin and clothing are quite high in the longer wavelengths mainly involved at these temperatures, around 0.98 and 0.95 respectively. The units for W_b are $\frac{W}{m^2}$, so to calculate the heat energy emitted by the human body, again assuming 33^oC mean skin temperature and $1.8\frac{m}{s^2}$ surface area

$$(\epsilon\sigma T^4)(A_D) =$$

$$0.98(5.7 \times 10^{-8}\frac{W}{m^2 \cdot {}^oK^4})(306^oK)^4(1.8\frac{m}{s^2}) = 880W$$

In reality, the human body does not radiate this much heat. Instead the human body absorbs a portion of its own thermal radiation as well as that of surrounding surfaces. When calculating radiant heat transfer from the human body (or small object) to a surrounding room (or large container), the following approximation is useful

$$R = \sigma\epsilon_1(T_1^4 - T_2^4)(\frac{A_r}{A_D})$$

where T_1 is the absolute temperature of the body, T_2 is the temperature of the room, ϵ_1 is the emittance of the body (approx. 0.98), and the ratio $\frac{A_r}{A_D}$ compares in the area exchanging radiative energy with the surroundings (A_r) to the total body surface area (A_D). This ratio is 0.65 for a body sitting and 0.75 for a body standing. The max value is 0.95 for a body spread eagled. Thus, for a naked man sitting in a 25^oC room,

$$Q'_{rad} = \sigma\epsilon_1(T_1^4 - T_2^4)(\frac{A_r}{A_D})A_D$$

$$= (5.7 \times 10^{-8}\frac{W}{m^2 \cdot {}^oK^4})(0.98)\times$$

$$((33 + 273^oK)^4 - (25 + 273^oK)^4)(.65)(1.8m^2) = 58W$$

Thus, 58-85W is a reasonable heat dissipated due to radiation. In a 15^oC room, 122-180W of dissipation may be expected.

Heat may also be re-gained by the body through radiation, in particular, solar radiation. Human skin and clothing have variable emissivity for many of the wavelengths generated by the sun (a 5760^oK source). In addition, the angle of the sun and orientation of the subject have significant effects on the heat transfer. However, empirical studies have shown that a semi-nude man walking in a desert has an effective 233W solar load. When light clothing is worn, this can be lessened to 117W [8].

2.3. Conduction

Conduction normally plays a small role in human heat regulation, except as the first stage of convection. Heat can be dissipated through contact with shoe soles, doorknobs, or through the surface underneath a reclining subject. Heat conduction through a wall of area A and thickness b is given by

$$Q'_{cond} = \frac{kA(T_1 - T_2)}{b}$$

where k is the thermal conductivity of the wall material and T_1 and T_2 are the wall temperatures. The sign of Q' indicates direction of heat flow.

2.4. Evaporation

When the body is sedentary, it loses heat during evaporation of water from the respiratory and from diffusion of water vapor through the skin (insensible or latent heat loss). When other modes of heat loss are insufficient, the body sheds excess heat through evaporation of sweat (sensible heat loss). The rate of heat lost through the evaporation process can be calculated by

$$Q'_{evap} = \Delta m \cdot \lambda$$

where Δm is the rate of mass of water lost and λ is the latent heat of evaporation of sweat ($2450\frac{J}{g}$). Thus, for typical water loss through the respiratory tract ($.008\frac{g}{s}$), the heat loss is $20W$. In hot environments, sweat rates can be as high as $0.42\frac{g}{s}$ for unacclimatized persons and $1.11\frac{g}{s}$ for acclimatized persons, resulting in $1000W$ to $2700W$ of heat dissipation respectively [5].

2.5. Heat storage

One term in equation 2 is still unexamined: Q'_{stor}. Heat storage in the body takes the form of a higher body temperature and can be calculated with the formula

$$S = mC\Delta T$$

where S is the energy stored, m is body mass, C is the specific heat of the body (approx. $3.5 \times 10^3\frac{J}{kg^oC}$), and ΔT is the change in body temperature. Thus, for a 1^oC increase in a 70kg man,

$$S = 70kg(3.5 \times 10^3\frac{J}{kg^oC})(1^oC) = 245,000J$$

of heat energy are stored. If this increase occurs over the course of an hour, the average power absorbed is $Q'_{stor} = 68W$. In this way the human body is its own buffer when adequate heat dissipation is not available or when too much heat is being dissipated.

2.6. Skin temperature, thermal receptors, and damage

Skin temperature may vary wildly depending on the area measured. For example, while comfortable, temperature readings on the toes may register 25^oC while the forehead is 34^oC [9]. Even temperatures within a small region may show significant variation due to air flow [5]. How these temperatures are perceived by the body depends on the range and the context of the temperatures. Table 1 (adapted from [8]) summarizes typical responses to skin temperatures. In general, the receptors in the skin are much more sensitive to changes in temperatures. Thus, momentary contact with a surface that is warmer than the skin will elicit a sensation that seems much hotter than would be felt with more constant contact. This, plus the fact that skin can be quite cool compared to normal body temperature, corresponds to the wide bounds on these ranges.

Table 1. Skin temperature sensations

Skin Temp. ^oC	*State*
45	tissue damage
43-41	threshold of burning pain
41-39	threshold of transient pain
39-35	hot
37-35	initial sense of warm
34-33	neutral
33-15	increasing cold
15-5	intolerably cold

While contact with any surface above 43^oC for an extended period of time risks burning, temporary contact can be made at higher temperatures. For 10 minutes, contact with a surface at a temperature of 48^oC can be maintained. Metals and water at 50^oC can be in contact with the skin for 1 minute without a burn risk. In addition, concrete can be tolerated for 1 minute at 55^oC, and plastics and wood at 60^oC. At higher temperatures and shorter contact times, materials show a higher differentiation of burn risk [9]

3. Thermal regulation in a forearm-mounted wearable computer

While the previous section discussed rules and principles in general, this section will concentrate on a specific example: a forearm-mounted wearable computer (inspired by BT's proposed "Office on the Arm" [2]). The goal is to model how much heat such a computer could generate if it is thermally coupled to the user. In order to perform this analysis, several conditions must be assumed.

First, the surface area of the forearm must be approximated. the forearm is about 3.5% of the body's surface area [8] or $0.063m^2$ for our assumed user. Note that this is approximately the surface area of the bottom of a smaller notebook computer. For convenience, it will be assumed that the computer fits snugly around the forearm as a sleeve for near perfect heat conduction and will have negligible thickness so that inner and outer surface areas will be approximately equal.

To provide an approximate bounds on the amount of heat the forearm computer can generate, the free air dissipation of heat through convection and radiation must be calculated. For practical considerations, the assumed environment will be a relatively warm, humid day of 31^oC (88^oF), relative humidity of 80%, and a maximum allowable surface temperature of the computer of 41.5^oC (or 106.7^oF, a temperature considered safe for long-term contact).

Using the guidelines from above

$$Q'_{conv} = h_c(A_{fore})(T_s - T_{amb})$$

$$Q'_{conv} = 2.68(41.5^oC-31^oC)^{0.25}(0.063m^2)(41.5^oC-31^oC)$$
$$= 3.2W$$

Assuming a surface emmitance of .95 and 80% of the surface of the forearm computer "seeing" the environment for radiative exchange

$$Q'_{rad} = R \cdot A_{fore}$$

$$Q'_{rad} = \sigma\epsilon(T_1^4 - T_2^4)(\frac{A_r}{A_D})(A_{fore})$$
$$= (5.7 \times 10^{-8}\frac{W}{m^2 \cdot {}^oK^4})(0.95)\times$$
$$((41.5 + 273)^4 - (31 + 273)^4)(0.80)(0.063m^2)$$
$$= 3.4W$$

Thus, in this environment, uncoupled from the body with no wind and no body motion, the forearm computer could produce 6.6W. Note that, from these calculations, an open laptop computer would have approximately twice this surface area with a resulting maximum free heat dissipation of 13.2W, close to the 12W of informal industry guidelines.

Table 2. Skin structure.

depth (mm)	*structure*
0-0.4	epidermis
0.5	superficial venous plexi
0.8	superficial arteriolar plexus
1.4	superficial venous plexi
2.2	subcutaneous fat begins
2.5	subcutaneous arteries accompanied by venae comitantes

However, once mounted on the arm, heat will also be conducted from the computer to the arm. At this point the analysis must become much more detailed to take into account the involved physiology and thermal gradient that will be produced in the arm. Table 2 (from [4]) shows the approximate depths of various skin features. Most thermal coupling that must be considered is through the skin ($0.37\frac{W}{m^oC}$ thermal conductivity [1]) to the surface veins and arteries. For this, a more complex model is needed to take into account the thermal gradient and mass transport.

3.1. Derivation of Heat Flow in the Arm

To begin, we define the fundamental heat flow rates [11] in the arm. See figure 1 for an explanation.

$$\begin{aligned} -(M'c_p)_1 dT_1 &= dQ'_{12} - dQ'_{in} & (1)\\ -(M'c_p)_2 dT_2 &= -dQ'_{12} + dQ'_{23} & (2)\\ -(M'c_p)_3 dT_3 &= -dQ'_{23} + dQ'_{out} & (3)\end{aligned}$$

where we define the heat flow rates as

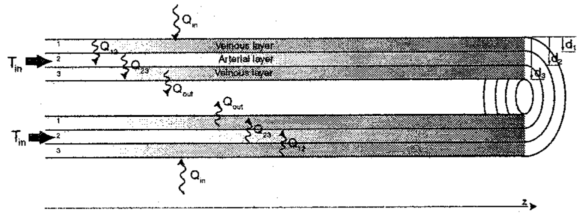

Figure 1. Blood flow geometries in the arm.

$$\begin{aligned} dQ'_{12} &= k(T_1 - T_2)dA_2 & (4)\\ dQ'_{23} &= k(T_2 - T_3)dA_3 & (5)\\ dQ'_{in} &= k(T_B - T_1)dA_1 & (6)\\ dQ'_{out} &= k(T_3 - T_{arm})dA_4 = 0 & (7)\end{aligned}$$

Equation 7 was set to zero to simplify the calculation. Since blood mass is conserved, arterial blood flow must return along the two venous layers. We can thus define the blood flow rates as

$$\begin{aligned} M'_1 &= -M'_2/p & (8)\\ M'_3 &= -M'_3/q & (9)\end{aligned}$$

where $1/p + 1/q = 1$.

To ease the computation, the above equations can be reformulated in terms of dimensionless parameters. Define $N = \frac{kA_2}{M'_2 c_p}$, $dA_i = A_i \frac{z}{L}$, $\xi = N\frac{z}{L}$, $\alpha = \frac{A_1}{A_2}$, $\beta = \frac{A_3}{A_2}$. Combining this with equations 1 through 9 yields

$$\begin{aligned} -\frac{dT_1}{d\xi} &= -p(T_1 - T_2) + p\alpha(T_B - T_1) & (10)\\ -\frac{dT_2}{d\xi} &= -(T_1 - T_2) + \beta(T_2 - T_3) & (11)\\ -\frac{dT_3}{d\xi} &= q\beta(T_2 - T_3) & (12)\end{aligned}$$

Let $\theta_i = \frac{T_i - T_B}{T_{in} - T_B}$. T_{in} is a constant to denote the temperature of the blood in the rest of the body as it flows into the artery of the arm. The derivative is $d\theta_i = \frac{T_i}{T_{in} - T_B}$. Finally this yields three dimensionless, coupled differential equations

$$\begin{aligned} \frac{d\theta_1}{d\xi} &= p\theta_1(1+\alpha) - p\theta_2 & (13)\\ \frac{d\theta_2}{d\xi} &= \theta_1 - \theta_2(1+\beta) + \beta\theta_3 & (14)\\ \frac{d\theta_3}{d\xi} &= -q\beta(\theta_2 - \theta_3) & (15)\end{aligned}$$

The general solution is of the form $\theta_i = \sum_{j=1}^{3} C_{i,j} e^{\lambda_i \xi}$. These equations can easily be decoupled in a matrix formalism. Rewriting the right side of equations 11 through 13 as a matrix, M, the eigenvalues of M are the λ_i's. Thus, solving the cubic equation

$$\begin{vmatrix} p(1+\alpha) - \lambda & -p & 0 \\ 1 & (1+\beta) - \lambda & \beta \\ 0 & -q\beta & -1 - \lambda \end{vmatrix} \qquad (16)$$

will yield each λ_i.

The remaining part of the solution entails applying the boundary conditions. The boundary conditions are:

- The blood entering the artery at the elbow is in contact with a large heat bath (the body) that maintains the blood temperature entering down the arm at 37°C.
- The blood mixes in the hand such that the blood temperature at the arm-hand junction is equal in the artery and two venous layers. In actuality, due to the hand, the exit temperature of the arterial flow will be slightly different (warmer) than the return venous flow. This boundary condition was imposed for simplicity and because it gives a lower bound on the heat exchange rate in the arm.

Mathematically, the first boundary condition can be written as

$$\theta_2(0) = C_{2,1} + C_{2,2} + C_{2,3} = 1 \qquad (17)$$

Including this in equations 13 through 15 yields

$$\begin{aligned} \frac{d\theta_1}{d\xi}(0) &= p\theta_1(0)(1+\alpha) - p & (18)\\ \frac{d\theta_2}{d\xi}(0) &= \theta_1(0) - (1+\beta) + \beta\theta_3(0) & (19)\\ \frac{d\theta_3}{d\xi}(0) &= -q\beta(1 - \theta_3) & (20)\end{aligned}$$

which further simplifies to

$$\begin{aligned} \sum_{j=1}^{3} C_{1,j}(1 + \alpha - \lambda_j) &= p & (21)\\ \sum_{j=1}^{3} C_{1,j} - \sum_{j=1}^{3} C_{2,j}\lambda_j + \beta\sum_{j=1}^{3} C_{2,j} &= 1+\beta & (22)\end{aligned}$$

$$\sum_{j=1}^{3} C_{3,j}(q\beta - \lambda_j) \;=\; q\beta \qquad (23)$$

The same can be done with the second boundary condition to yield

$$\sum_{j=1}^{3} C_{1,j}e^{\lambda_j N} - \sum_{j=1}^{3} C_{2,j}e^{\lambda_j N} \;=\; 0 \qquad (24)$$

$$\sum_{j=1}^{3} C_{1,j}e^{\lambda_j N} - \sum_{j=1}^{3} C_{3,j}e^{\lambda_j N} \;=\; 0 \qquad (25)$$

Combining these results with equation 13 through 15 also yields

$$\sum_{j=1}^{3} C_{1,j}e^{\lambda_j N}(\lambda_j - p\alpha) \;=\; 0 \qquad (26)$$

$$\sum_{j=1}^{3} C_{2,j}e^{\lambda_j N}(\lambda_j) \;=\; 0 \qquad (27)$$

$$\sum_{j=1}^{3} C_{3,j}e^{\lambda_j N}(\lambda_j) \;=\; 0 \qquad (28)$$

Equations 17 and 21 through 28 can be combined into a matrix to evaluate the constants

$$M \cdot C = B$$

$$M = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ \gamma_1 & \gamma_2 & \gamma_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & \lambda_1 & \lambda_2 & \lambda_3 & \beta & \beta & \beta \\ 0 & 0 & 0 & 0 & 0 & 0 & \chi_1 & \chi_2 & \chi_3 \\ \upsilon_1 & \upsilon_2 & \upsilon_3 & -\upsilon_1 & -\upsilon_2 & -\upsilon_3 & 0 & 0 & 0 \\ \upsilon_1 & \upsilon_2 & \upsilon_3 & 0 & 0 & 0 & -\upsilon_1 & -\upsilon_2 & -\upsilon_3 \\ \upsilon_1\mu_1 & \upsilon_2\mu_2 & \upsilon_3\mu_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \upsilon_1\lambda_1 & \upsilon_2\lambda_2 & \upsilon_3\lambda_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \upsilon_1\lambda_1 & \upsilon_2\lambda_2 & \upsilon_3\lambda_3 \end{bmatrix}$$

$$C = \begin{bmatrix} C_{1,1} \\ C_{1,2} \\ C_{1,3} \\ C_{2,1} \\ C_{2,2} \\ C_{2,3} \\ C_{3,1} \\ C_{3,2} \\ C_{3,3} \end{bmatrix}, B = \begin{bmatrix} 1 \\ p \\ 1+\beta \\ q\beta \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where $\upsilon_i = e^{\lambda_i N}$, $\gamma_i = 1 + \alpha - \lambda_i$, $\chi_i = q\beta - \lambda_i$, and $\mu_i = \lambda_i - p\alpha$. The constants become $C = M^{-1} \cdot B$ and a final solution is obtained.

The actual physical data used to solve this problem is listed below:

- T_{in}=37°C, T_B=39°C.
- p = q = 2.
- k=0.37 $\frac{W}{m^oC}$[1].
- $d_1 = 0.0005m$, $d_2 = 0.0008m$, and $d_3 = 0.0014m$.
- Average arm skin surface area = 0.063 m^2 and the average radius of the arm is 0.035 m [5].
- Blood flow was calculated for a few values from the range of possible[5] blood flows in the arm (5,10,15, and 22 $\frac{ml}{100ml_{skin} \cdot min}$).

The average power transfer into the arm can be calculated by taking the mean integral of the temperature distribution in the outer vein and modifying equation 6:

$$Q'_{in} = k(T_B - \langle T_1 \rangle)A_1 \qquad (29)$$

where $\langle T_1 \rangle = \frac{T_{in} - T_B}{N} \int_0^N \theta_1 d\xi + T_{in}$

The power results for the different blood flows are shown in Table 3.

Table 3. Heat dissipation for various blood flow rates

Blood flow rate ($\frac{ml}{100ml_{skin} \cdot min}$)	*Power (W)*
5	2.96
10	5.92
15	8.87
22	12.90

Note that these power ratings increase linearly with the difference $T_B - T_{in}$. Since heat dissipation depends linearly on blood flow, an obvious question is what sort of blood flow can we expect at 41.5^oC? Skin blood flow is increased to an area both when the local temperature of that part is raised or when the body temperature as a whole is elevated [5]. If enough heat is transferred from the forearm to the rest of the body to cause a noticeable rise in temperature, other parts of the body will begin heat dissipation techniques as well. Skin blood flow is regulated by vasodilation and vasoconstriction nerves. Areas that act as heat sinks, like the hands, have almost exclusively vasoconstriction nerves. Larger areas, such as the forearm have a mixture. In cold conditions, blood is pumped through the arteries and returned through the deeper veins. When the body temperature rises or when heat or an irritant is applied to the local area, blood is shunted to the surface veins to increase body cooling. Skin blood flow in the forearm has been measured at 22ml per 100ml of skin per minute [5], and conversations with current researchers in the field suggest even higher blood flow rates.

3.2. Verification of the model

To verify the model in the last section, an experiment examining the conduction of heat away from the forearm was performed. Two open-topped 10 liter styrofoam containers were filled with water at 48.8^oC and placed side by side in a 25^oC temperature-controlled room. Magnetic stirrers were used to keep the water agitated. Two calibrated digital thermometers were placed diagonally across from each other in each bath. When the baths cooled to 43^oC, the subject immersed his forearm into the "forearm bath," leaving his upper arm and hand out of the bath. The temperatures of both the forearm and control baths were recorded every 200 seconds until the baths cooled below body temperature. The subject was dressed in t-shirt, jeans, and boots. Before the experiment, he indicated he was overly warm even after remaining seated for an hour. Before and during the experiment, his body temperature remained constant and no visible perspiration was evident, though he claimed his forehead felt moist before immersion and during the early part of the experiment.

For each 200 second time period, the heat loss of each bath was calculated using the temperature corrected thermal capacity of water (approx. $4.179\frac{J}{g^oC}$) [15]. The result can be seen in Figure 2. By interpolating the corresponding heat loss at a given temperature for the control water bath, the difference in heat loss between the two baths can be calculated. Figure 3 shows the increase in heat dissipation caused by conduction through the forearm.

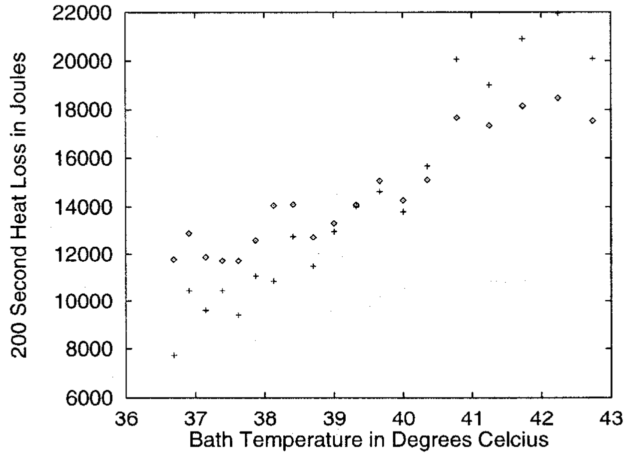

Figure 2. Heat dissipation from forearm (+) and control (o) water baths.

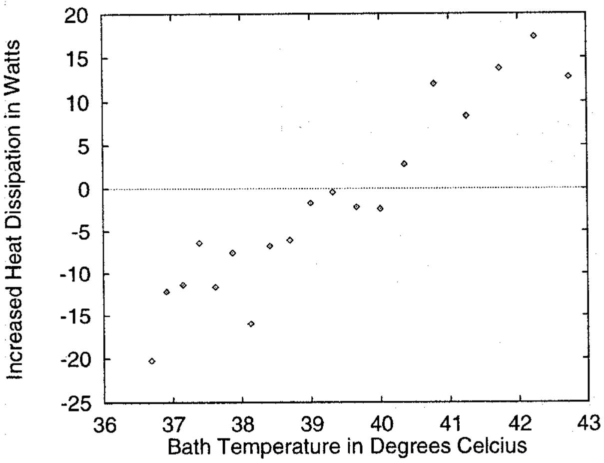

Figure 3. Heat conduction through forearm versus water bath temperature.

Note that there is a distinct "knee" in the graph at approximately 40.5^oC. Above this temperature, the forearm bath seems to dissipate, on average, 12.8W more heat than the control bath. Under 40^oC the forearm bath is actually dissipating less than the control path. Such a drastic change would be expected under 37^oC. Indeed, in this regime the forearm seems to be heating the water, but why would such a sudden change happen around 40^oC? First, the amount of blood that is pumped to the surface veins and arteries of the forearm decreases, in general, as temperature decreases. A similar breakpoint is observed in the literature [5] for blood flow at this temperature. However, even given that the blood flow may be significantly reduced at these temperatures, why should the presence of the forearm inhibit heat dissipation before the water bath reaches body temperature? A possible explanation is that the forearm was blocking the radiative, convective, and evaporative heat dissipation of the bath. Since the forearm was submerged just below the surface of the bath, the covering water could not mix with the main body of water to transfer heat. From the graph, the forearm seems to be blocking approximately 10W of heat loss at 37^oC that the control bath was experiencing, implying an even higher rate at higher temperatures! Thus, the total heat conducted away by the forearm may be > 20W at 41.5^oC. For future experiments, a thermally neutral dummy arm of the same volume should be inserted into the control bath and both baths should be agitated more aggressively.

While this experiment involved one subject, the results coincide with temperature vs. blood flow experiments from the literature and also correlate nicely with the model proposed above. Thus, using a conservative blood flow of 10 $\frac{ml}{100ml\cdot min}$, the model in Equation 29 predicts at least 13.3W of heat should be dissipated by the body with a forearm computer maintained at 41.5^oC. The experiment Note that since the body is very active in maintaining its core temperature, this amount of heat dissipation from the forearm may be available in all but the most adverse conditions.

3.3. Practical limits and issues

Given the above models and calculations, a forearm computer may generate up to

$$Q'_{tot} = Q'_{conv} + Q'_{rad} + Q'_{cond} = 18.8W$$

This is summarized in Figure 4 and is more than twice the heat dissipation per surface area capability of a normal notebook computer. Of course, the wearable would need to monitor its surface temperature to avoid exceeding the $41.5^{\circ}C$ limit. However, this calculation ignores several practical factors. The most obvious is the feeling of a $41.5^{\circ}C$ sheath on the forearm. A simple way to address this is to provide the user with a knob to adjust the maximum operating temperature of the computer (up to safe limits). This explicitly trades computation power with heat dissipation. Note that, since the quoted results are conservative, the system may dissipate a good amount of heat even at lower temperatures. Secondly, the body may sweat due to exertion. Without a way for sweat to be released, the user may experience discomfort, similar to the sensation of sweating in rubber gloves. To alleviate this problem, a thin layer of heat conducting fabric can provide the additional function of "wicking" the water trapped under the computer sleeve. "Slits" should be designed into the computer to allow evaporation of the water. These slits provide a fringe benefit of adding more surface area.

By tightly thermally coupling the computer to the user's forearm, intermittent contacts of the surface with other body parts may be better tolerated. The user has an innate sense that the computer can not be burning him or else his forearm would be uncomfortable. This helps offset the effects of different relative temperatures of the skin surface.

The above analysis is for a reasonably constrained situation. In actuality, the user's thermal environment will change, often to the benefit of the computer. Small amounts of air flow can significantly increase heat dissipation. While walking, the air flow about the arm is significantly enhanced by the pendulum-like movement of the arm. In fact, the air flow along the forearm is effectively turbulent for many situations, effectively doubling the heat dissipation of calmer air movement. [5]. Changes in ambient and skin temperature and the cooling effects of the user's sweating may be exploited in many cases (for example, when a sweating user enters an air conditioned building). With sensing of skin temperature and sweating, the forearm computer can regulate its own heat production according to the thermal environment. The temperature feedback mechanisms already common in microprocessor design point to such a trend.

More aggressive systems might employ active thermal regulation. For example, the heat capacity of the computer's batteries might be exploited. While charging, batteries might also be chilled so that heat can be transferred into them during processing [3]. Heating the batteries may also provide the benefit of increasing battery life. By employing active cooling elements such as Peltier junctions, the computer might cool the batteries or components during times of low ambient temperature. Thus, the computer has access to a thermal reservoir during times of heat stress. Finally, software applications can be written with heat dissipation in mind. Disk maintenance, downloads, and batch jobs can be delayed until the computer senses a cooler environment. In this manner, performance is reserved for user interactions, and the effective average heat dissipation can be higher.

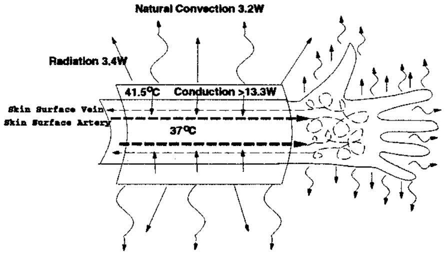

Figure 4. Forearm computer heat dissipation.

Evenly distributing heat from the microprocessor's surface to the conducting surface of the computer's case can not be done with a simple metal plate. Instead, a variant of a heat pipe will be needed. Heat pipes are fully closed evaporative systems. Water contacts the hot surface, is vaporized, and convects to the cooler side of the heat pipe. Upon contact, the water vapor condenses and is absorbed by a wick which transports the water back to the hot surface via capillary action. Such a system uses a miniscule amount of water and is highly effective at transporting heat. In practice, the actual computer in the forearm sheath may be the size of a credit card with the rest of the casing dedicated to the distribution of heat. By making these sections modular, fashionable casings could be designed to complement the user's wardrobe. More discussion on the advantages and disadvantages of these methods can be found in the corresponding technical report to this paper [14].

3.4. Other locations for mounting

Mounting the computer on the forearm has many advantages including convenient access, higher availability of turbulent air flow due to the pendulum effect, and heat exchange through the hand. However, the legs have a similar set of advantages with an even larger surface area. While the system is designed to operate with skin regions at body temperature, in practice, mounting the computer on "core" body areas will result in a lower temperature gradient and less heat dissipation compared to the extremities. However, mounting on the head has the advantage of faster natural convective air flow while the user is sedentary and a constant flow of forced air while walking. Unfortunately, hair impedes heat conduction to the skin.

4. Discussion

The placement of a wearable computer or any consumer electronic depends greatly on its function, expected time of use, and physical characteristics. Mounting locations may include the hands, head, back, chest, waist, hips, legs, and feet. For light systems that generate heat, placement where skin contact is available is recommended. The head has excellent air convection properties, but hair thermally decouples the system from the skin. Placement along the trunk of the body limits heat dissipation from the body's core and can be functionally and socially inconvenient to place next to the skin. Leg placement provides a broad surface area for skin conduction and benefits from the pendulum effect for air convection but may be inconvenient for access. Feet have the benefit of good air convection and accessibility but have little skin surface area. Thus, the forearms provide a good compromise: good skin conduction, excellent air convection, and functional and social accessibility.

For hot and heavy systems, such as for the military, great care must be taken in placement and thermal conduction. Large loads require that the system be carried on the trunk, but air convection flow is mainly laminar in this region if the user is standing still and the packs prevent a relatively large skin surface area from dissipating heat normally. If the user is in a cool environment, the large surface area provides an opportunity to dissipate a significant amount of heat through body conduction/convection to the limbs. Sensible sweating will probably occur in many environments, and the system should be designed to use this water for cooling and move the water away from the skin to prevent heat rash. However, for these higher heat loads, the wearer should be carefully monitored for heat stress. Such systems are more appropriate for military and hazardous area situations and should be carefully tested before field use.

5. Conclusion

This paper provides first-order heat dissipation guidelines for developing wearable computer prototypes and introduces an unconventional way of thinking about cooling. By thermally coupling a forearm wearable computer with the user, heat dissipation can be significantly increased from today's industry limits, even in warm environments. For military and hazardous applications, systems may dissipate even more heat if there is careful monitoring of the user and the environment.

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