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# *Heat Loss during Surgical Skin Preparation*

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***Background:*** **Hypothermia develops rapidly during the 1st h of anesthesia and results in part from evaporative heat loss during surgical skin preparation. The authors tested the hypothesis that evaporation of skin preparation solution contributes significantly to hypothermia.**

***Methods:*** **Five healthy, unanesthetized volunteers were studied in a 22 ± 0.4° C environment. One thigh of each volunteer was washed for 10 min, using each of the following representative solutions: (1) water; (2) 50% ethanol in water (EtOH/$H_2O$; similar to tincture of iodine); and (3) povidone-iodine gel. Water and EtOH/$H_2O$ each were tested at ambient temperature (cold), warmed to 40° C before application (warm), and with radiant heating of the skin, and gel only at ambient temperatures, resulting in seven study states. Heat loss and skin temperatures on the washed thighs were measured using thermal flux transducers, and values compared with the data obtained from the contralateral unwashed thighs. Change in mean body temperature (per 70 kg) due to washing was calculated by integrating measured heat loss over time and multiplying by the specific heat of human tissue. A mathematical model was developed to predict cutaneous heat loss using only skin temperature, independent of the type and temperature of skin-preparation solution or the use of radiant heating during preparation.**

***Results:*** **Heat loss from the unwashed thigh was ≈14 kcal/$m^2$ during radiant warming and ≈39 kcal/$m^2$ without warming. Net heat loss (increment produced by washing) was ≈30 kcal/$m^2$ with water and gel without radiant warming, but loss was larger with EtOH/$H_2O$ than with water under all study conditions. Radiant warming reduced total heat loss (increment produced by washing and environment) during both the EtOH/$H_2O$ and water trials, compared with warm or cold EtOH/$H_2O$ and water alone. The calculated decreases in mean body temperature per 70 kg ranged from −0.2 to −0.7° C/$m^2$. The smallest decrease occurred during radiant warming and washing with water, and the largest decreases during warm or cold EtOH/$H_2O$.**

***Conclusions:*** **Heat loss was significantly less with water-based than with alcohol-based solutions. Though heating the solutions and radiant warming decreased heat loss, such loss under each tested condition, even per square meter of washed surface, was small compared to other causes of perioperative hypothermia. Consequently, the authors recommend that efforts to maintain intraoperative normothermia be directed elsewhere. (Key words: Heat, loss: evaporation; radiation. Heat, measurement: thermal flux transducers. Hypothermia. Models, theoretical: evaporation; heat loss; thermoregulation. Temperature, measurement: skin.)**

PERIOPERATIVE hypothermia results, in part, from evaporation of surgical skin-preparation solution.§ The heat of vaporization of water is 578 kcal/kg; thus, evaporation of only 100 g water-based preparation solution would decrease mean body temperature ≈1° C in a typically sized patient.[1] In contrast, direct conductive heat loss is unlikely to contribute significantly to overall heat balance: warming 100 ml of water-based solution from 20° C to 37° C requires only 1.7 kcal and would decrease mean body temperature ≤0.03° C.

The amount of fluid evaporating during surgical skin preparation is unknown but depends on vapor pressure of the solution and scrubbing technique, as well as ambient temperature, humidity, and air speed. The heat of vaporization differs substantially in available formulations (*e.g.*, water-based *vs.* ethanol/water combinations), making general predictions of evaporative loss difficult. Furthermore, evaporative heat loss cools the skin, thereby limiting further evaporative loss, while simultaneously reducing radiative and convective losses.

Radiant warming has been recommended to minimize evaporative heat loss during skin preparation.[2] However, warming likely increases the important evaporative loss while reducing the much smaller conductive

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§ Flacke JW, Flacke WE: Inadvertent hypothermia: Frequent, insidious, and often serious. Seminars in Anesthesia 2:183–196, 1983.

and convective loss. The extent to which the additional required heat of vaporization is supplied by radiant warming *versus* the skin cannot be predicted easily. Other authors suggest that warming the skin-preparation solution before application may decrease conductive and evaporative heat loss.[3] Yet this technique may not markedly decrease total heat loss because: (1) conductive loss is a small fraction of the total, and (2) warm solution will evaporate rapidly, reducing the temperature of solution remaining on the skin.

In the present study, we tested the hypotheses that: (1) Evaporation of surgical skin-preparation solution significantly reduces mean body temperature. (2) Radiant skin-surface warming during surgical preparation reduces total heat loss. (3) Warming of the preparation solution has little effect on total heat loss. Additionally, we developed a mathematical model to predict heat loss from skin temperature; the resulting formula does not depend on the type of solution or its temperature and remains valid during application of radiant heating.

## Methods

With approval from the University of California, San Francisco, Committee on Human Research, we studied five healthy volunteers. No volunteer was obese or taking medications. During each study, the volunteers reclined on a standard operating room table covered with a circulating water mattress set at 42° C (Blanketrol II, Maxi-Therm blanket #276, Cincinnati Sub-Zero, Cincinnati, OH). Ambient temperature was maintained at 22 ± 0.4° C, air speed at ≈20 cm/s (model FMA-602-V, Omega Engineering, Stamford, CT), and relative humidity at 42 ± 4% (model HX92, Omega Engineering). All refrained from coffee or alcohol before and during study periods but snacked lightly during the sessions. Three days typically were required to complete the protocol in each volunteer.

### *Study Protocol*

We tested three representative skin-preparation solutions: (1) water (similar to Betadine, Purdue Frederick, Norwalk, CT); (2) 50% ethanol in water (EtOH/$H_2O$; similar to tincture of iodine); and (3) povidone-iodine gel (E-Z Prep, Solo Prep Topical Gel, Becton Dickinson, Franklin Lakes, NJ). The gel contains povidone-iodine detergent solution with 1% available iodine. To minimize the risks of chemical burn, we used solvent alternatives to Betadine and tincture of iodine. Although dissolved iodine would increase the vapor pressure of the solvents slightly, the heat of vaporization would change little because the relatively volatile, and far more numerous solvent molecules would evaporate first. The heat of vaporization is 578 cal/g for water and 263 cal/g for EtOH.

We tested water and EtOH/$H_2O$ under three study conditions: (1) test solution at ambient temperature (cold); (2) test solution warmed to 40° C in a water bath (warm); and (3) ambient-temperature solution accompanied by radiant warming (radiant; IMI model 4000, FYE Medical, San Bruno, CA) set at 39° C and positioned 53 cm above and parallel to the legs. The povidone-iodine gel was tested only at ambient temperature because the package insert recommends against warming the solution. Consequently, seven trials were performed in each volunteer.

The anterior surface of one thigh was prepared for study by outlining a 10 × 25-cm rectangle. Each trial was preceded by a 10-min control period (−25 to −15 elapsed min), followed by an additional control period of 15 min (−15–0 elapsed min) or 15 min of radiant warming, if appropriate.

Starting at 0 elapsed min, the skin inside the prepared rectangle on the test thigh was washed with one of the test solutions for 10 min using standard techniques (0–10 elapsed min). The skin was washed using cloth-covered cotton balls held with forceps; at ≈2-min intervals, the cotton ball was discarded and replaced with a fresh ball moistened with the test solution. Care was taken to limit the spread of solution to the 10 × 25-cm test area and to keep the solution tray well away from the radiant warmer. Solution remaining on the skin after the final application was allowed to evaporate for 30 min (10–40 elapsed min).

Treated and unwashed thighs were chosen randomly for each trial, as was the order in which solutions were tested. After each trial, the treated thigh was cleaned, dried, and again allowed to equilibrate with the ambient environment. Sufficient time was allowed between trials to assure that control heat loss from each thigh was comparable and similar to loss during previous sessions with that volunteer.

### *Measurements*

The test solution, tray, forceps, and cotton applicator balls were weighed immediately before and after each 10-min washing period using a Setra model 5000L scale (Acton, MA), which has an accuracy of 0.01 g over the range 0–5,000 g. The amount of solution used in each trial was calculated by comparing the weights before

and after washing. Preliminary studies established that little solution evaporated from the tray during the washing period.

Heat loss was measured in $W/m^2$ using two thermal flux transducers[4] (Concept Engineering, Old Saybrook, CT) placed on the anterior surface of each thigh. When wet (as on the treated thigh), flux transducers measure total heat loss (*e.g.*, conductive, convective, radiative, and evaporative). The thermal resistance of these transducers is quite small ($0.0059° C \cdot m^{-2} \cdot W^{-1}$) and thus minimally impedes transfer of heat from the skin to the evaporative surface of the unit. We defined flux as positive when heat traversed skin to the environment. We have described the details of thermal flux measurements previously.[5] (The basal metabolic rate in adult humans is $\approx$100 W and 1 W = 0.86 Kcal/h.)

Skin-surface temperatures were monitored using thermocouples incorporated into the thermal flux transducers. Thermocouples were connected to an IsoThermex (Columbus Instruments International, Columbus, OH) 16-channel electronic thermometer having an accuracy of 0.1° C and a precision of 0.01° C.

*Data Analysis*

Data were recorded in 64-s epochs starting every 2.5 min.[6] A database program was used to sort and average data recorded from each volunteer into 5-min epochs. When performing these analyses, we gave equal statistical weight to data from the different volunteers. The individual averages then were used to calculate the means for all volunteers in a given study state.

Heat flux and temperatures from the two sites on each thigh were averaged. Loss from each thigh during 10 min of skin preparation and the subsequent 30 min of drying (0–40 elapsed min) were calculated by numeric integration and converted to kilocalories. Net loss was determined by subtracting heat loss on the treated thigh from that on the unwashed thigh during each trial. It thus represents the incremental loss from the unwashed condition, with or without radiant warming, produced by washing with each solution. The amount of water or $EtOH/H_2O$ evaporated during each trial was estimated using the assumption that net loss resulted entirely from solution vaporization. No estimate of evaporative loss was obtained for gel since the manufacturer was unwilling to provide us with the composition of the product or its heat of vaporization.

Total loss was calculated by subtracting loss on the treated thigh from the average loss on the unwashed thigh during trials without radiant warming. Total loss thus represents the loss produced by washing and the environment (with or without radiant warming), compared with unwashed skin without radiant warming. Unlike net loss, total loss depends on the duration of the drying period when radiant warming is used (*i.e.*, net and total loss diverge over time even without skin washing). From total loss, predicted change in mean body temperature was calculated using a tissue specific heat of $0.83\ kcal \cdot kg^{-1} \cdot ° C^{-1}$.[1]

Data were compared using repeated-measures analysis of variance and Dunnett's tests. Data at the end of the control period (−20 to −15 min) were considered reference values for time-dependent data within each trial. Data for water were considered reference values when comparing among the three solutions. Similarly, data from unwarmed trials were considered reference values when comparing among warming methods for each solution. Results are reported as means ± SD; differences were considered significant when $P < 0.05$.

We then constructed a mathematical model of evaporative heat loss (Appendix). The resulting equation related variation in equilibrium temperature at various tissue depths to variation in skin temperature:

$$U(x,t) = \frac{2}{\sqrt{\pi}} \int_{\frac{x}{2\sqrt{Dt}}}^{\infty} U\left(t - \frac{x^2}{4D\beta^2}\right) e^{-\beta^2} d\beta, \qquad (1)$$

where $U(x,t)$ (° C) is the variation in temperature at distance x from the surface at time $t$ (h), $U(t)$ (°C) is the variation in skin temperature at time $t$, and D ($cm^2/h$) is the thermal diffusion constant. Similarly, we derived an equation relating cutaneous heat loss to skin-surface temperature:

$$F(t) = \rho s \sqrt{\frac{D}{\pi}} \int_0^t \frac{\frac{dU(t')}{dt'}\, dt'}{\sqrt{(t - t')}}, \qquad (2)$$

where $F(t)$ ($cal \cdot cm^{-2} \cdot h^{-1}$) is cutaneous heat loss at time $t$, $\rho$ ($g/cm^3$) is the density, and s ($cal \cdot g^{-1} \cdot ° C^{-1}$) is the specific heat.

We made a piece-wise linear fit of the experimentally determined temperatures *versus* time (25–35 and 35–40 min). These coefficients were then employed in equation 2 to predict cutaneous heat loss, using the flux at −5–0 elapsed min as the integration constant. The value of D was taken to be 5.3 $cm^2/h$ as derived in the Appendix (equation A3).

## Results

The volunteers were 31 ± 11 yr of age, 167 ± 18 cm tall, and weighed 64 ± 16 kg. Three of the five were female. The skin appeared dry at the end of each trial involving water and EtOH/$H_2O$, whereas a rubbery coating remained on the skin after the gel trials.

Heat loss and skin temperatures from the thigh washed with each representative solution (water, EtOH/$H_2O$, and gel) at ambient temperature are shown in figure 1. Loss increased significantly throughout washing, and the increase was largest with EtOH/$H_2O$. Loss remained increased during washing, but returned toward control values after 10 min of drying. Skin temperatures decreased most during washing with EtOH/$H_2O$, and least with gel. By the end of the 30-min drying period, however, none of the skin temperatures had returned to control values.

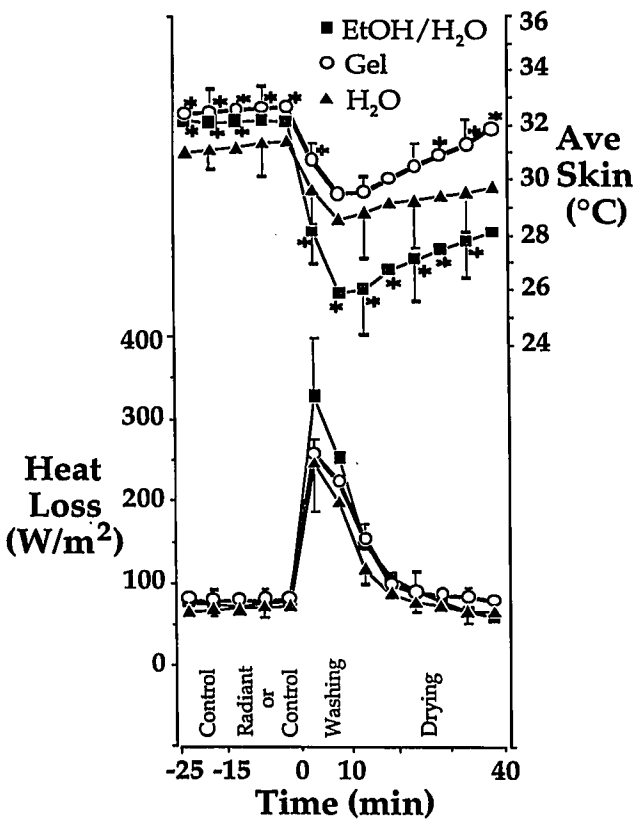


**Fig. 1. After a 25-min control period, a 10 × 25-cm rectangle on one thigh of each volunteer was washed for 10 min with one of three representative skin-preparation solutions: (1) water (similar to Betadine); (2) 50% ethanol in water (EtOH/$H_2O$; similar to tincture of iodine); and (3) povidone-iodine gel. Skin temperature and cutaneous heat loss in W/m² (determined using thermal flux transducers) were measured under control conditions (−25–0 elapsed min), skin washing (0–10 elapsed min), and subsequent 30 min of drying (10–40 elapsed min). Heat loss from 0–15 elapsed min was significantly different from control values. All skin temperatures after 0 elapsed min were significantly different from control values. Asterisks indicate significant differences from water.**

Heat loss and skin temperatures with cold water, warm water, and cold water with radiant warming are shown in figure 2. Radiant heat significantly decreased cutaneous loss before skin washing and significantly increased loss during washing. Loss remained increased throughout washing in all volunteers, but returned toward pre-washing values after 10 min of drying. As expected from the flux data, radiant warming significantly increased skin temperatures before skin washing (−15–0 elapsed min) and significantly decreased temperatures during washing. Temperatures remained low throughout washing, returning toward control (or radiant) values after 15 min of drying. Nonetheless, skin temperatures remained warmer throughout study with cold water and radiant warming than with either cold or warm water alone.

Washing with warm water decreased skin temperatures only slightly less than that with cold water. Patterns of heat loss and skin temperatures with cold EtOH/$H_2O$, warm EtOH/$H_2O$, and cold EtOH/$H_2O$ with radiant warming were similar to those observed with water, but exaggerated (fig. 3).

Values for integrated heat loss from the treatment and unwashed thighs, net heat loss, solution used, total heat loss, and the estimated decrease in mean body temperature during each treatment are provided in table 1. Heat loss (0–40 elapsed min) from the unwashed thigh was ≈14 kcal/m² during radiant warming and ≈39 kcal/m² without warming. Net heat loss (increment produced by washing) was similar with cold water and gel without radiant warming; net heat loss was greater with EtOH/$H_2O$ than water and gel under all study conditions.

Radiant warming reduced total loss (increment produced by washing and environment) during both the EtOH/$H_2O$ and water trials, compared with warm or cold EtOH/$H_2O$ and water alone. The calculated decreases in mean body temperature per 70 kg ranged from −0.2 to −0.7° C/m². The smallest decrease occurred during radiant warming and washing with water, and the largest decreases during warm or cold EtOH/$H_2O$. The weights of water and EtOH/$H_2O$ used exceeded the estimated evaporative amount by approximately fourfold (*e.g.*, 47 *vs.* 197 g for unwarmed water).

Figure 4 shows that there was good concordance between the cutaneous heat loss predicted by our mathematical model and the measured results. The relation between predicted and measured values was quantified by using linear regression between 5 and 40 elapsed min: the correlation coefficient, r, was between 0.9 and 0.95 in each example shown in figure 4. A quadratic, rather than linear, fit to the temperature data made only a small difference in the predicted heat flux. Similarly, the predicted heat loss was relatively insen-

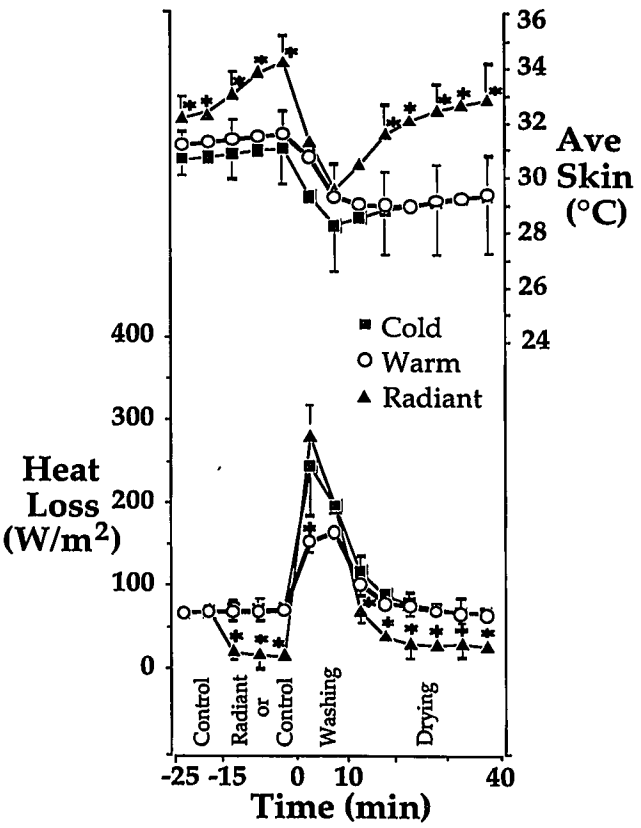


Fig. 2. After a 10-min control period followed by 15 min of radiant warming or of additional control conditions, a 10 × 25-cm rectangle on one thigh of each volunteer was washed for 10 min with water under three different conditions: (1) at ambient temperature (cold), (2) warmed before application (warm), and (3) at ambient temperature with radiant warming of the skin (radiant). Skin temperature and cutaneous heat loss were measured during the control period (−25 to −15 elapsed min), radiant warming or additional control conditions (−15–0 elapsed min), skin washing (0–10 elapsed min), and the subsequent 30 min of drying (10–40 elapsed min). Heat losses for cold and warm water from 0 to 15 elapsed min were significantly different from control values. Heat loss during radiant warming was significantly different from control values at all elapsed times after −15 min, except for the 10–15-min epoch. Skin temperatures for cold and warm water after 0 elapsed min were significantly different from control values. Skin temperatures during radiant warming were significantly different from control values from −15–15 elapsed min. Asterisks indicate significant differences from cold. Skin temperatures during the control period preceding radiant warming were statistically, but not clinically, significantly different from cold water.

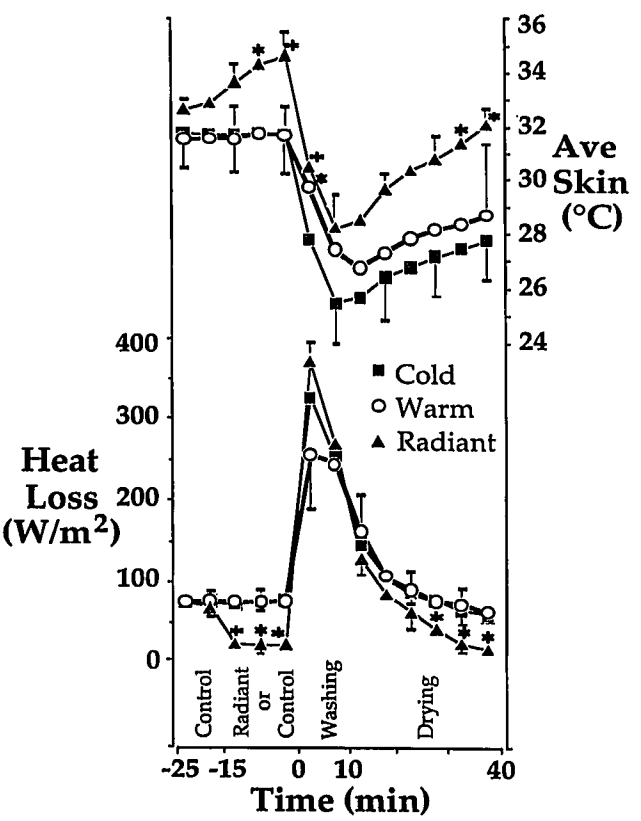


Fig. 3. After a 10-min control period followed by 15 min of radiant warming or of additional control conditions, a 10 × 25-cm rectangle on one thigh of each volunteer was washed for 10 min with 50% ethanol in water ($EtOH/H_2O$) under three different conditions: (1) ambient temperature (cold), (2) warmed before application (warm), and (3) ambient temperature with radiant warming of the skin (radiant). Skin temperature and cutaneous heat loss were measured during the control period (−25 to −15 elapsed min), radiant warming or additional control conditions (−15 to 0 elapsed min), skin washing (0–10 elapsed min), and subsequent 30 min of drying (10–40 elapsed min). Heat losses for cold and warm $EtOH/H_2O$ from 0 to 15 elapsed min were significantly different from control values. Heat loss during radiant warming was significantly different from control values at all elapsed times after −15 min, except for the 10–20-min epochs. Skin temperatures for cold and warm $EtOH/H_2O$ after 0 elapsed min were significantly different from control values. Skin temperatures during radiant warming were significantly different from control values after −15 elapsed min. Asterisks indicate significant differences from cold.

**Table 1. Heat Loss, Weight of Solution Used, and Estimated Change in Mean Body Temperature**

| | Treated Loss ($kcal/m^2$) | Unwashed Loss ($kcal/m^2$) | Net Loss ($kcal/m^2$) | Total Loss ($kcal/m^2$) | Solution Used ($g/m^2$) | Change in Mean Body Temperature/ 70 kg (° $C/m^2$) |
|---|---|---|---|---|---|---|
| Cold $H_2O$ | 66 ± 12 | 37 ± 12 | 28 ± 7 | 27 ± 12 | 197 ± 60 | −0.4 ± 0.2 |
| Warm $H_2O$ | 56 ± 5 | 39 ± 4 | 17 ± 6* | 17 ± 5 | 270 ± 28 | −0.3 ± 0.1 |
| $H_2O$, radiant | 51 ± 9 | 14 ± 4* | 37 ± 5 | 12 ± 9* | 272 ± 80 | −0.2 ± 0.1* |
| Cold EtOH/$H_2O$ | 81 ± 14* | 37 ± 6 | 44 ± 14* | 42 ± 14* | 405 ± 143* | −0.7 ± 0.2* |
| Warm EtOH/$H_2O$ | 80 ± 18* | 41 ± 9 | 39 ± 12 | 41 ± 18* | 520 ± 30* | −0.7 ± 0.2* |
| EtOH/$H_2O$, radiant | 73 ± 8 | 13 ± 6* | 60 ± 6* | 34 ± 8 | 513 ± 54* | −0.6 ± 0.1 |
| E-Z Prep Gel | 71 ± 14 | 40 ± 8 | 31 ± 12 | 32 ± 14 | 189 ± 82 | −0.5 ± 0.2 |

Integrated heat loss from the treated and unwashed thighs, net heat loss (increment produced by washing), total loss (increment produced by washing and environment), weight of solution used, and estimated change in mean body temperature for each trial. Data from 0 to +40 elapsed min were integrated. The trials were as follows: (1) water at ambient temperature ("Cold $H_2O$"); (2) water warmed before application ("Warm $H_2O$"); (3) $H_2O$ applied during radiant warming of the skin ("$H_2O$, radiant"); (4) 50% EtOH in $H_2O$ at ambient temperature ("Cold EtOH/$H_2O$"); (5) 50% EtOH in $H_2O$ warmed before application ("Warm EtOH/$H_2O$"); (6) 50% EtOH in $H_2O$ applied during radiant warming of the skin ("EtOH/$H_2O$, radiant"); and (7) E-Z Prep Gel applied at ambient temperature.

* Significant difference from cold $H_2O$.

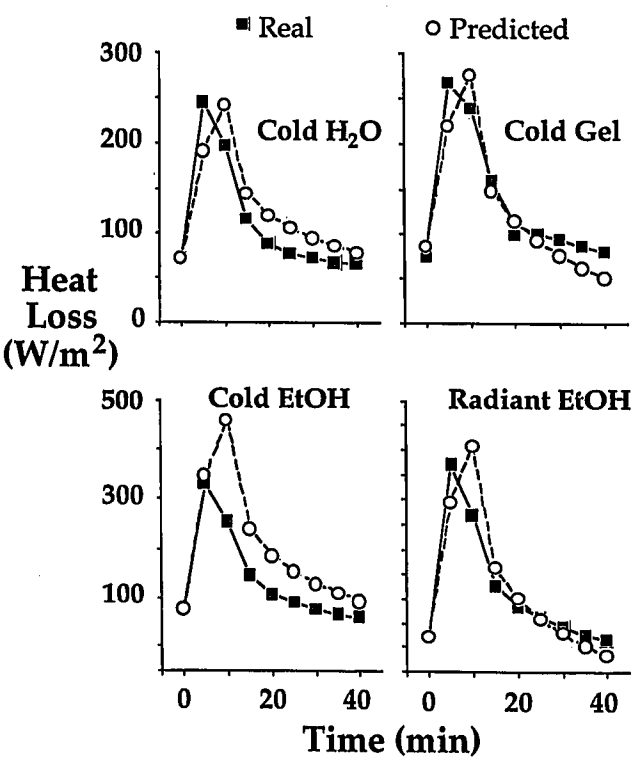


**Fig. 4. Measured heat flux compared with flux predicted from our mathematical model during washing with cold water, cold 50% ethanol in water (EtOH/$H_2O$), cold gel, and EtOH/$H_2O$ with radiant heating. The model predicts cutaneous heat loss from skin-surface temperature using slab geometry and the assumptions that the thermal diffusion coefficient, tissue heat production, and cutaneous blood flow remain constant during the test period. There was good agreement between predicted and measured values.**

sitive to the choice of thermal diffusion coefficient (D), as can be seen from equation 3. The experimental data were better fit when D was taken as 3.0, a value for human skin determined more accurately than the rough calculation described in the Appendix.[6]

## Discussion

We developed our model of evaporative heat loss by assuming that the heat of vaporization is supplied by the skin and subcutaneous tissues. Using a form of the standard bioheat equation, we further assumed that D and heat production (H) were constant over the relatively short study. Using known values of density and tissue specific heat, we first roughly determined the diffusion coefficient from steady-state heat loss. Determined values for D and H agreed with previous results.[7] Using these values, we estimated tissue cooling depth, from which we predicted surface cooling during skin washing. Predicted and measured skin-surface cooling values were comparable.

Encouraged by these rough estimates, we developed a more sophisticated model. Slab geometry was chosen because the estimated tissue cooling depth was small compared with the curvature of most body segments. Given surface temperature, this model predicts temperature at all depths and cutaneous heat loss. The model is summarized in equations 1 and 2. There was good agreement between the model and measured values, suggesting that our assumptions and approximations were reasonable.

The model assumes slab geometry, which probably is a good approximation for most prepared surfaces. The disparities between measured and predicted heat loss more likely result because the model also assumes that the thermal diffusion of the washed skin and adjacent tissues remains constant during the experimental period. This is only approximately correct. In fact, the model can be extended to include variation of the coefficient in time (spatial variation is more complicated to include). However, we believed that the additional complexity required to introduce more parameters (and therefore making a better fit between measured and predicted data) was unwarranted. And finally, our model does not include changes in net heat production or blood-borne transport of heat during the relatively short period of skin preparation.

The clinical significance of the model is that it allows prediction of cutaneous heat loss from measured skin temperatures independently of skin-preparation solution characteristics. Thus, heat loss from evaporation of newly developed solutions can be determined from surface temperature. Furthermore, heat loss under other circumstances can be determined from these general equations. For example, heat loss from inside surgical incisions, which would be difficult to measure in humans, could be estimated using this model and appropriate assumptions.

The constituents of E-Z Prep gel are proprietary, but the solution appears to be water-based since net and total heat losses were similar with water and gel (cold solution, no radiant warming). In contrast, far more heat was lost with the EtOH/$H_2O$ solution than with water under similar test conditions. Ethanol has a considerably higher vapor pressure than does water at typical skin temperature (77 *vs.* 32 mmHg, respectively). Additionally, operating rooms often have a relative humidity near 40%, which further slows evaporation of water-based solutions. Thus, at a given skin temperature, the ethanol portion of the EtOH/$H_2O$ solution will evaporate more rapidly than the water fraction. Our data are consistent with these expectations: heat loss during skin washing with EtOH/$H_2O$ was significantly greater than with water, and most of the difference occurred during the washing period (when ethanol was constantly provided by freshly moistened cotton balls).

Radiant warming significantly decreased heat loss from 70 ± 6.6 to 19 ± 10 W/$m^2$ before skin washing. During both water and EtOH/$H_2O$, heat loss increased more during radiant warming than during other study conditions. However, when the 10-min washing period was completed, loss rapidly returned to its initial low level. Consequently, net loss was highest during radiant warming, whereas total heat loss was lowest. The decrease in total heat loss was clinically significant, especially with water, where loss was reduced 66% compared with cold solution without radiant warming. However, in a typical clinical setting in which radiant warming is not continued during 30 min of drying, there would be less difference between the treatments.

The change in mean body temperature was estimated from total heat loss because total loss best reflects the effects of washing with each solution with or without radiant warming. Values ranged from −0.2 to −0.7° C/$m^2$. Any reduction in body heat content eventually must be replenished, frequently *via* postanesthetic shivering.[8,9] However, an acute reduction in body heat content by cutaneous cooling may not immediately decrease central temperature. Just as central-to-peripheral redistribution hypothermia requires 30–40 min,[10,11] cutaneous thermal manipulations may require nearly an hour to alter central temperature in vasodilated individuals.[12] (In vasoconstricted patients, even major changes in cutaneous heat transfer may not be reflected in central temperature for more than 1.5 h.[13])

Our results are expressed per square meter of surgical skin preparation. This is an extensive area and would require washing almost the entire anterior surface of a typically sized (70 kg) supine patient. Even fairly large preparation areas (*e.g.*, 45 × 45 cm) represent only 0.2 $m^2$ and would thus produce only one-fifth the heat loss indicated in table 1. Losses would be even less were the skin blotted dry immediately after washing. Heat loss and change in mean body temperature can be estimated in other clinical situations (*e.g.*, infants and children) using our values, the washed surface area, and the patient's weight. Losses with other solutions can be estimated from measured skin temperatures using our model. It is unlikely that differences in age or gender would alter our results substantially.

Evaporative loss theoretically could be distinguished from radiant, conductive, and convective heat transfer by weighing the solution receptacle, forceps, and cotton applicator balls before and after skin washing. However, estimated weights of evaporated skin-preparation solutions typically were approximately one-quarter the weight used. These apparently contradictory values might suggest an error in heat flux measurements or unaccounted loss in the test solutions. More likely, the difference results because dry stratum

corneum can absorb a considerable amount of water.[14] (Ethanol presumably is absorbed into the skin with even greater facility.) The difference between estimated and measured solution used would be explained by a 10% increase in moisture content of the top millimeter of the tested skin area. Thus, it is likely that much of the test solution used in each trial was absorbed into the skin and did not evaporate during the test period. Had we calculated heat loss using the assumption that all the solution used evaporated, loss would have been overestimated significantly.

We washed the skin on one thigh (and used the other for unwashed measurements) because the legs provided a large, bilaterally symmetric, area. Results in other parts of the body might differ. However, in any region, our model indicates that skin-surface temperature would be the major factor determining evaporative heat loss; we previously demonstrated that regional skin temperatures in vasodilated individuals are relatively uniform.[15]

Ambient temperature was controlled to ≈22° C in this study. Control heat loss certainly would be higher at lower ambient temperatures. However, cool skin would decrease evaporative loss during washing and drying. It is unlikely that small variations in operating room temperature (and the range of typical temperatures is small) would produce clinically significant alterations in total loss.

Heat loss from skin preparation was relatively small compared with total loss reported during the 1st h of typical surgical procedures.[12] Similarly, the calculated decrease in mean body temperature resulting from skin preparation also was relatively small under all study conditions. Heat losses were reduced slightly by warming the preparation solutions. However, the benefit probably does not outweigh the dangers of warming iodine-containing solutions (the manufacturers of Betadine and E-Z Prep both caution against such warming). Similarly, radiant warming decreased heat losses. Our data suggest that the benefits probably are not sufficient to make the practice routine. Consequently, we recommend that mixtures be applied to most patients at ambient temperature without radiant warming. Although infants are at greater risk of evaporation-induced hypothermia than adults (and easier to warm *via* cutaneous heating), they also have thinner skin, which may be especially susceptible to chemical irritation. Consequently, we suggest that particular caution be used if radiant skin heating or solution warming is applied to these patients.

In summary, we measured heat loss during cutaneous preparation with three different solutions under a variety of circumstances. From these data, we developed a mathematical model to predict heat loss from skin temperature; the resulting formula does not depend on the type of solution, its temperature, or application of radiant heating. Net heat loss (increment produced by washing) was ≈30 kcal/m$^2$ with water and gel without radiant warming, but loss was larger with EtOH/$H_2O$ than with water under all study conditions. Radiant warming reduced total loss (increment produced by washing and environment) during both the EtOH/$H_2O$ and water trials, compared with warm or cold EtOH/$H_2O$ and water alone. The calculated decreases in mean body temperature per 70 kg ranged from −0.2 to −0.7° C/m$^2$. The smallest decrease occurred during radiant warming and washing with water, and the largest decreases during warm or cold EtOH/$H_2O$. Loss under each tested condition, even per full square meter of washed surface, was small compared to other causes of perioperative hypothermia. Consequently, we recommend that efforts to maintain intraoperative normothermia be directed elsewhere.

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## References

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## Appendix

In this section we develop a framework in which the data can be interpreted. We state simple arguments and progressively develop a more sophisticated analysis providing better predictions of cutaneous heat loss.

### *Rough Arguments*

Radial heat flow within a cylindrical body segment (such as the thigh) is governed by

$$\frac{\partial T}{\partial t} - \left(\frac{D}{r}\frac{\partial T}{\partial r} + D\frac{\partial^2 T}{\partial r^2} + \frac{\partial D}{\partial r}\frac{\partial T}{\partial r}\right) = H, \tag{A1}$$

where $H(r,t)$ in ° C/h denotes the net temperature change per unit time at a point $(r,t)$ due to anything other than diffusive heat flow, including metabolic production of heat and the transport of heat by blood flow. Thermal diffusivity, $D(r,t)$, is given in $cm^2/h$; axial or longitudinal heat transfer is neglected.

Taking D and H as constants (which is a reasonable approximation over a short period of surgical skin preparation), we have the time-independent solution:

$$T(r) = T_{Core} - \frac{H}{4D}r^2, \tag{A2}$$

where $T_{Core}$ is core body temperature. In this equilibrium, the heat flow out, $F(cal \cdot cm^{-2} \cdot h^{-1})$ is given by

$$F = -K\left.\frac{\partial T}{\partial r}\right|_{surface},$$

$$F = \rho s \frac{H}{2} r_s, \tag{A3}$$

where we have used the thermal conductivity K ($cal \cdot cm^{-1} \cdot ° C^{-1} \cdot h^{-1}$) = $\rho s D$, where $\rho$ ($g/cm^3$) is the density, s ($cal \cdot g^{-1} \cdot ° C^{-1}$) is the specific heat, and $r_s$ (cm) is the radius of the thigh.

We can use equations A2 and A3 to determine constants H and D. Taking $\rho s$ = 0.83 $cal \cdot cm^{-3} \cdot ° C^{-1}$, $r_s$ = 8 cm, and having measured $F$ at (about) 75 $w/m^2$, from equation A3, $H$ = 2.0° C/h. Taking $T_{Core}$ = 37° C and $T_{skin}$ = 31° C, we obtain, from equation A2, D = 5.3 $cm^2/h$. These are similar to previously reported values.‖

Now the approximate effect of skin preparation on heat loss can be determined. A substance that can evaporate when upon the skin absorbs heat from the body, thereby lowering skin temperature. The net loss for $EtOH/H_2O$ was about 40 $kcal/m^2$. Pure ethanol has a heat of vaporization of 263 cal/g; thus, the net amount of ethanol vaporized was 3.8 g, and the time required for vaporization was about 0.25 h.

From the net loss of $F$ = 4.0 $cal/cm^2$ and the fact that the heat transfer in the body is analogous to a diffusion process, we can compute the depth, Δr, within the body from which the heat came. For a diffusion process,

$$\frac{(\Delta r)^2}{2Dt} \approx 1. \tag{A4}$$

From D = 5.3 $cm^2/h$ and t = 0.25 H, we deduce $\Delta r \approx 1.6$ cm.

We can now calculate the decrease in temperature due to evaporative cooling from the heat balance, so

$$(\Delta r)\rho s(\Delta T) = F. \tag{A5}$$

Thus, ΔT = 3.0° C, which is in good agreement with the measurements.

### *Determination of the Cooling Depth*

As we saw in the previous section, the heat for vaporization comes from the top 1–2 cm of the body. Consider the temperature difference $U(r,t)$ between the true temperature $T(r,t)$ and the equilibrium temperature distribution given by equation A2. Clearly, then, $U(r,t)$ satisfies the homogeneous diffusion equation

$$\frac{\partial U}{\partial t} - \left(\frac{D}{r}\frac{\partial U}{\partial r} + D\frac{\partial^2 U}{\partial r^2}\right) = 0. \tag{A6}$$

Since the heat only comes from a small tissue depth, Δr compared to $r_s$, we can use slab geometry, so

$$\frac{\partial U(x,t)}{\partial t} - D\frac{\partial^2 U(x,t)}{\partial x^2} = 0, \tag{A7}$$

where $x$ is distance into the slab.

We can use this equation to study how $U$ varies in depth and time. Suppose $U$ is zero everywhere, and then at t = 0, suddenly the surface of the body is made temperature $T_0$ (for evaporative cooling, $T_0$ might be −3.0° C). How does $U$ vary? The solution is well known and is

$$U(x,t) = T_0 \mathrm{Erfc}\left(\frac{x}{2\sqrt{Dt}}\right), \tag{A8}$$

where *Erfc* is the complement of the error function, defined as

$$Erfc(w) = \frac{2}{\sqrt{\pi}}\int_w^\infty e^{-u^2}du, \tag{A9}$$

$$U(x,t) \to T_0\left[1 - \frac{x}{\sqrt{\pi Dt}}\right]; \text{ x small, t large}$$

$$U(x,t) \to \frac{T_0 2}{x}\sqrt{\frac{Dt}{\pi}}e^{\frac{-x^2}{4Dt}}; \text{ x non-zero, t small.} \tag{A10}$$

Near the surface, the temperature varies linearly with depth into the body (and the distance "in" increases as $\sqrt{t}$); whereas at large distances, $U$ is sensibly zero; *i.e.*, there is no effect from surface cooling.

‖ Ducharme MB, Tikuisis P: In vivo thermal conductivity of the human forearm tissues. J Appl Physiol 70:2682–2690, 1991.

We now can obtain a good estimate of the effective depth, $\Delta r$, introduced in the last section. From

$$T_0(\Delta r) = \int_0^\infty U(x,t)dx. \tag{A11}$$

After integrating by parts and using equations A8 and A9, we obtain

$$\Delta r = \frac{2}{\sqrt{\pi}} \int_0^\infty x dx \frac{e^{-\frac{x^2}{4Dt}}}{2\sqrt{Dt}}. \tag{A12}$$

Performing the integration, we get

$$\Delta r = \frac{2}{\sqrt{\pi}} \sqrt{Dt} = \sqrt{\frac{2}{\pi}} \sqrt{2Dt}. \tag{A13}$$

In the previous section we used $\Delta r = \sqrt{2Dt}$, so we were only in error by employing $\Delta r = 1.41\sqrt{Dt}$ rather than $\Delta r = 1.12\sqrt{Dt}$.

### *Slab Model*

The above considerations can be generalized to arrive at a model for evaporative cooling of a patient during surgical skin preparations. Suppose we have a slab extending, as before, from $x = 0$ to $x = \infty$, and suppose initially $U(x,t)$ is everywhere zero.

Now suppose a surface temperature $U(t)$ is imposed for $t \geq 0$. The resulting temperature distribution was described by Byerly in 1893#:

$$U(x,t) = \frac{x}{2\sqrt{\pi D}} \int_0^t \frac{U(t')e^{-\frac{x^2}{4D(t-t')}}}{(t-t')^{3/2}} dt'. \tag{A14}$$

# Byerly WE: Fourier's Series, Boston, Gin, 1893, p 88.

This can be put into a more convenient form by letting

$$\beta = \frac{x}{2\sqrt{D(t-t')}}, \tag{A15}$$

so

$$U(x,t) = \frac{2}{\sqrt{\pi}} \int_{\frac{x}{2\sqrt{Dt}}}^\infty U\left(t - \frac{x^2}{4D\beta^2}\right) e^{-\beta^2} d\beta. \tag{A16}$$

In this form it is easy to see that, as $x \to 0$, $U(x,t) \to U(t)$. It also is easy to show that $U(x,t)$ satisfies the homogeneous diffusion equation (equation A7).

We now can evaluate the flow of heat from the skin due to evaporative cooling. From equation A3, we need to evaluate

$$\left.\frac{\partial U}{\partial x}\right|_{x=0}.$$

The limit is tricky, but after some algebra, one obtains

$$F(t) = \rho s \sqrt{\frac{D}{\pi}} \int_0^t \frac{\frac{dU(t')}{dt'} dt'}{\sqrt{(t-t')}}. \tag{A17}$$

Equations A16 and A17 constitute our model. Given a temperature distribution on the skin surface $U(t)$, one can determine the temperature distribution within the body $U(x,t)$ [$U(x,t)$ is the variation from equilibrium], and one can determine the flow of heat, $F(t)$, from the body.