Adapting Adult Scald Safety Standards to Children

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Scald burns by domestic tap water constitute a painful, potentially debilitating, and sometimes-fatal form of thermal injury. In this setting, the very young and older members of the population are particularly susceptible, owing in part to having thinner skin, which renders them more susceptible to thermal insult. Various codes have set forth a safety standard for maximum delivery temperature of domestic tap water at 120°F (48.9°C), based on adult susceptibility to burns. This work addresses the issue of how the current safety standard for tap water temperature could be adjusted to provide a level of protection to children equivalent to that for an adult at 120°F. A well-accepted mathematical model for predicting burn injury as a function of applied surface temperature and time is used to identify these equivalent conditions. Data from the literature of sonographic measurements indicate a representative ratio of child to adult skin thickness of 0.72. The mathematical model shows that the equivalent surface temperature for a threshold scald injury in children is dependent on the depth into the skin at which the injury is identified. For example, the injury produced by a 120°F, 10-second exposure at a depth of 600 μm in an adult is matched in a child at 72% of the depth (432 μm) by an insult of 115.9°F for the same duration. The recommendation is that existing hot water standards be reduced by 3 to 4°F to provide an equivalent level of scald protection to children. (J Burn Care Res 2006;27:314–322)
The adaptation of the mathematical model for the present study required identifying features and properties that distinguish adult and child skin. Of greatest relevance for predicting thermal burns is the differential in skin thickness. Ultrasonic imaging techniques make it possible to measure the thickness of skin non-invasively and in situ, opening the possibility of acquiring greater quantities of skin thickness data more accurately than in the past. This type of data has been published recently and was used in the present study.

One of the major challenges in this study was to identify an appropriate and rational format for interpreting the differences in the model simulations for children and adults. The model predictions of the extent of injury as defined by Henriques and Moritz are based on the application of a constant temperature source onto the surface of the skin for the entire duration of the insult process. The temperature value as input to the mathematical model is defined at the skin surface, although it is interpreted in terms of the depth to which the injury is propagated at first, second or third degree levels. This interpretation is based on an exemplar skin thickness typifying that of an adult. The injury manifestation process resulting from a defined thermal insult will be different for the skin of a child owing to its thinner structure. Comparison of the thermal damage at differing depths requires a nonlinear algorithm because applied heat diffuses into the skin as a wave having a magnitude that diminishes with depth. The transient nature of the heating process also means that quantitative comparison is dependent on the duration of the surface thermal insult, which can be evaluated in comparison with the time constant for movement of the thermal wave to a specified depth in the skin. Thus, to complete the comparison of burns in child and adult skin it is necessary to specify a target time of exposure for the insult. The analysis presented in this paper defines and addresses all the above aspects of the issue of determining a temperature standard for scald safety for children. The hypothesis of this study is that a standard Arrhenius mathematical model for scald burns can be adapted to produce an injury to a representative child as does 120°F to a representative adult.

SCALD BURN
MATHEMATICAL MODEL

Human skin has a layered structure consisting of a thin superficial epidermis, an underlying dermis that is often 10 to 20 times thicker, and an even thicker layer of subcutaneous fat. Thermally, this structure behaves as a composite material in which heat is conducted sequentially through the adjacent layers. The dermis has a rich microvascular network that provides for convective heat transfer with the tissue in which it is embedded but at the elevated temperatures associated with a burn injury the perfusion is terminated rapidly. Thus, heat transfer internal to the skin in the core region of a burn can be assumed to be exclusively via conduction.

The initial step in establishing a mathematical model for heat transfer and the resulting burns in the skin is to characterize the skin as a physical system in which an appropriate coordinate structure can be fixed. The duration of a scald burn is quite short (normally limited to tens of seconds maximum) in comparison with the time that would be required to cause a significant rise in temperature in subdermal tissue (anticipated to be many minutes). Thus, the transient temperature field can be limited to within the skin structure.

The anatomy of the skin consists of a very thin overlying epidermal layer and a much-thicker underlying dermal layer. Although the epidermis presents a critical barrier to injury and has a critical physiological role in determining the depth and characteristic of a burn injury, from a heat transport perspective its thermal diffusion properties are only slightly distinguished from those of dermis, and its relative thickness is quite small. Therefore, the differential thermal properties that it may have in comparison with the dermis will be neglected, allowing the system to be treated as having homogeneous thermal properties. This assumption simplifies solution of the governing transport equations considerably.

In many scald burns, the lateral extent of the burned area is measured on a length scale of centimeters, whereas the depth of the thermally affected tissue more than an order of magnitude thinner. This small depth/breadth aspect ratio justifies the assumption that from a local perspective spatial gradients in the temperature field are far greater normal to the skin surface. Further, the thickness of the skin is very small in comparison with the radius of curvature of the skin surface over nearly all sites on the body. These aggregate assumptions lead to the addressing the heat transfer and burn processes as varying along a single Cartesian coordinate into the skin, which reduces to the problem of one-dimensional transient heat transfer into a semi-infinite medium, as illustrated in Figure 1. The governing transport equation for this problem and its solution are very well defined in the literature and will be applied for the present analysis.

The temperature within the skin, \( T(x, t) \), is a function of position, \( x \), and time, \( t \), according the thermal

\[ \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \]

where \( \alpha \) is the thermal diffusivity of the skin.
diffusion equation.
\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}
\]  
where \(\alpha\) is the thermal diffusivity. The thermal boundary condition at the skin surface can be specified either in terms of an applied constant temperature or convection with flowing water. In the limiting case of highly effective convection, the boundary condition will approach that of an applied temperature. Because this solution will result in a worst-case burn injury, it is adopted for this analysis and specified as \(T(x, 0) = T_s\). The far field and initial uniform temperatures in the skin are both equal, \(T_i\). The analytical solution for this problem is expressed as the error function.\(^{11}\)

\[
T(x, t) = T_i - \frac{T_s - T_i}{\text{erf} \left( \frac{x}{2\sqrt{\alpha t}} \right)}
\]  

The mathematical description of the temperature given in equation 2 is applied to calculate the local rate of thermal damage, which then is integrated over the total time of the insult to yield a net level of injury. The damage rate is assumed to occur as a protein denaturation, which can be described in terms of an Arrhenius process kinetics model. The quantitative rate of accumulation of injury is calculated in terms of a function denoted by \(\Omega\).

\[
\frac{d\Omega_i(x, t)}{dt} = Ae^{-\frac{\Delta E}{RT_i}}
\]

The total injury after a time \(\tau\) of thermal insult is obtained by integrating eq. (3) over that period.

\[
\Omega(x, \tau) = \int_0^\tau \frac{d\Omega_i(x, t)}{dt} dt = A \int_0^\tau e^{-\frac{\Delta E}{RT_i}} dt
\]  

The values for the scaling factor, \(A\), and the activation energy, \(\Delta E\), are derived from experimental data for thermal damage processes executed over the range of temperatures of interest. These types of experiments and analysis have been conducted by numerous investigators since the initial work of Henriques and Moritz.\(^1,2\) Although many alternative sets of coefficients exist and have been compared,\(^1,2,12,13\) the most frequently applied set for relatively low temperature injuries is that of Henriques and Moritz, which will be used here. These values along with that of the universal gas constant, \(\mathcal{R}\), are given in Table 1. Both equations 2 and 4 were easily solved via a simple Excel spreadsheet (Microsoft, Seattle, WA) for the range of states and properties of interest.\(^1,14,15\) The numerical results achieved are presented in the following section.

**RESULTS**

To compare the scalding process in adults and children, it is first necessary to define how the relevant physiological features and properties are distinguished. The two primary differences are most logically the thickness of the skin and its thermal properties. There is no data existent that points to a significant differential between the thermal conductivity, density, and/or heat capacity of child and adult skin.\(^10\) Therefore, the operational feature that differentiates between child and adult skin is taken as the thickness. Thinner skin will be more susceptible to scald injury because a given level of thermal insult applied at the surface will cause damage through a larger fraction of the total skin thickness.

Ultrasonic imaging technology has provided a noninvasive method of obtaining data on dermal thickness at virtually any targeted location on the body. In particular, Seidenari et al\(^9\) have recently published measurements of skin thickness in children and

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**Table 1. Values for the constitutive properties in the Arrhenius thermal damage model (equation 4)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Universal gas constant, (R)</td>
<td>(8.31 \times 10^3) J/kmol K</td>
</tr>
<tr>
<td>Activation energy for thermal injury, (\Delta E)</td>
<td>(6.27 \times 10^3) J/kmol</td>
</tr>
<tr>
<td>Scaling factor for Arrhenius injury function, (A)</td>
<td>(3.10 \times 10^3) 1/s</td>
</tr>
</tbody>
</table>
Table 2. Data from Sendari et al.9 for measurements of skin thickness (mm) in children and adults

<table>
<thead>
<tr>
<th>Location</th>
<th>2–3 Years</th>
<th>25–40 Years</th>
<th>Child/Adult Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead</td>
<td>1.18 ± 0.22</td>
<td>1.99 ± 0.34</td>
<td>0.59</td>
</tr>
<tr>
<td>Cheek</td>
<td>1.15 ± 0.12</td>
<td>1.84 ± 0.27</td>
<td>0.63</td>
</tr>
<tr>
<td>Upper abdomen</td>
<td>1.28 ± 1.21</td>
<td>2.01 ± 0.32</td>
<td>0.64</td>
</tr>
<tr>
<td>Interscapular region</td>
<td>1.48 ± 0.26</td>
<td>2.34 ± 0.26</td>
<td>0.63</td>
</tr>
<tr>
<td>Volar forearm</td>
<td>0.98 ± 0.10</td>
<td>1.30 ± 0.24</td>
<td>0.75</td>
</tr>
<tr>
<td>Dorsal forearm</td>
<td>1.18 ± 0.12</td>
<td>1.45 ± 0.24</td>
<td>0.81</td>
</tr>
<tr>
<td>Elbow crease</td>
<td>0.86 ± 0.10</td>
<td>0.98 ± 0.10</td>
<td>0.88</td>
</tr>
<tr>
<td>Lower leg</td>
<td>1.23 ± 0.14</td>
<td>1.49 ± 0.23</td>
<td>0.83</td>
</tr>
<tr>
<td>Average</td>
<td>1.17</td>
<td>1.68</td>
<td>0.72</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.19</td>
<td>0.45</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Measurements were made at all indicated sites for each subject. The adult population consisted of 30 subjects and the child population of 42 subjects inclusive of ages 2 to 13. The number within the two to three subgroups is not indicated.

adults at eight different sites. Their data are summarized in Table 1 for indicated measurement sites in adult and child populations. Although many domestic hot water burns occur to children younger than 2 years of age, the Seidenari et al. data set contains no information for subjects in that age bracket, nor are there data for subjects older than 40; therefore, the elderly also are excluded from the study. The skin data show a gradual increase in thickness from birth to adulthood. As shown in Table 2, the ratio of thickness for ages 2 to 3 and 25 to 40 was calculated at each of the eight measurement sites, and these values were averaged to identify a value of 0.72 with a standard deviation of 0.11. Although data are presented for older children, the values of thickness are larger. Furthermore, younger children tend to be more susceptible to scald injury because of their relative inability to control and respond to their environments. The variation among the measurement sites was 16% in children and 27% in adults. For purposes of the present analysis, it was assumed that the skin of children was 72% the thickness of adults.

An extended series of simulations was conducted in which transient temperatures were calculated via equation 2 at combinations of relative depths in the ratio of 1:0.72, and thermal damage was determined via equation 4 to identify the combinations of scald temperatures that produced the same levels of injury at each set of depths for a common insult period. The model equations dictate that at all depths below the skin surface the equivalent injury will occur in thinner skin at a lower temperature for an identical duration of exposure. Although the range of actual exposure times for domestic hot water scalds may vary widely, for determining a universal safety standard, it is necessary to choose a representative value that typifies the thermal environments of greatest concern. Data has been presented for the distribution of exposure times in showers and baths that lead to domestic hot water scalds.16 These data are presented as escape times from a shower and a bath and are defined as a function of age for a geriatric population. This type of information is sparse and is not known to exist for children. In lieu of alternative sources, the aforementioned data were extrapolated to children for the present analysis, resulting in a representative value for escape and, therefore exposure, time of 10 seconds.

The benchmark standard for scald safety temperature is 120°F, as has been defined in numerous codes in the United States, such as the International Plumbing Code as presented by the International Code Council.17 Therefore, the quantitative level of injury incurred at various depths in adult skin for a 120°F scald will be applied to define the temperature that produces the same injury at the same relative depth in child skin. These comparisons are generated directly via the solution of equations 2 and 4.

Figure 2 presents a plot of the transient temperatures in the skin at varying depths after a step change in the surface temperature from 34°C to 48.9°C (120°F). With increasing depth, the thermal response to the change in surface temperature is more delayed, slower, and diminished in magnitude. Thus, in comparing the thermal behavior of child and adult skin, both the rapidity and level of the temperature elevation will be more severe in children, resulting in a higher burn potential. Figure 3 is a complementary plot of the spatial temperature gradient in the skin before, during, and after the application of a step increment in surface temperature. During the insult period, the temperatures decrease progressively and nonlinearly from the surface. After removal of the surface heating source, the temperature wave continues to move further into the skin, but at a decreased level as energy is stored in the local tissue structures. Again, the obvious conclusion is that sites more proximal to the surface will experience a greater level of thermal stress.

The temperature/time data generated by solving equation 2 is applied in equation 4 to calculate the level of injury accrued at any given depth position by integrating over the duration of the insult process (10
Extensive simulations were run to show that there is no significant accrual of damage in tissue after insult after the temperature drops approximately 1°C from the peak local value. Given that the most extensive injury occurs closest to the skin surface where the response to changes in the boundary conditions is most rapid, for the sake of a simplified analysis and interpretation, all simulations were terminated at the end of the 10-second insult period.

Figure 4 presents a plot of how injury develops over time.

Figure 2. Predicted transient temperature profiles as a function of skin depth after a step change in surface temperature from 34°C to 48.9°C.

Figure 3. Predicted spatial temperature gradients at four times as a function of skin depth after a step change in surface temperature from 34°C to 48.89°C for 10 seconds followed by a return of the surface to 34°C.
time at incremental depths in the skin during a 10-second, 48.9°C scald scenario. The most striking feature of these data is the very large decrease in the level of injury at any time with increasing depth into the skin. Alternatively stated, at any given elapsed time more superficial locations have a significantly higher level of injury. Because the absolute depth for a child skin is only 72% that of adult skin for an equivalent structural position, the obvious implication is that the level of injury will be proportionately greater for the child.

Given the foregoing data for temperatures and injury levels generated as a function of skin depth for the benchmark 120°F scald insult, the challenge is to develop a strategy that enables the insult conditions to produce equivalent levels of injury at identical relative depths in the child and adult skin mathematical models. A relevant question to address is how much lower is the scald temperature that produces the same level of injury in a child as does 120°F in adults. The analysis shows that there is not a single specific answer. Changes in the scalding temperature applied at the surface do not translate into linearly proportional changes in the depth of the resulting burn. The difficulty arises from the facts that the thermal wave penetrates into the skin as a nonlinear function equation 2 and the resulting injury is a highly nonlinear function of the local temperature equation 4. Thus, reducing the scald temperature does not produce a decrease in injury that is linearly proportional with depth. Each insult temperature less than 120°F issues in a level of injury (Ω) that is identical for a unique set of matching relative child and adult skin depths. Identification of a scald temperature for children that will cause the same injury as does 120°F in adults requires that the relative depth be specified, and for each value of the relative depth there is an associated unique scalding temperature for children.

Simulations were run for a series of incrementally decreasing scald temperatures, and for each temperature the depth was identified for which the same level of injury occurred in child skin as does 120°F in an adult. The analysis shows that there is not a single specific answer. Changes in the scalding temperature applied at the surface do not translate into linearly proportional changes in the depth of the resulting burn. The difficulty arises from the facts that the thermal wave penetrates into the skin as a nonlinear function equation 2 and the resulting injury is a highly nonlinear function of the local temperature equation 4. Thus, reducing the scald temperature does not produce a decrease in injury that is linearly proportional with depth. Each insult temperature less than 120°F issues in a level of injury (Ω) that is identical for a unique set of matching relative child and adult skin depths. Identification of a scald temperature for children that will cause the same injury as does 120°F in adults requires that the relative depth be specified, and for each value of the relative depth there is an associated unique scalding temperature for children.

Simulations were run for a series of incrementally decreasing scald temperatures, and for each temperature the depth was identified for which the same level of injury occurred in child skin as would occur in adult skin at the equivalent fractional depth for a 120°F scald. Figure 5 presents a compilation of the sets of skin depths and scald temperatures that produce injury levels in the child skin mathematical model that are identical to those at an equivalent fractional depth in adult skin for a scald at 120°F.

**DISCUSSION**

The absolute values of the injury function shown in Figure 4 are considerably smaller than the thresholds for first and second degree burns (0.53 and 1.0, respectively). However, the present simulation was terminated after only 10 seconds. Henriques’ data and model results² from which the current mathematical
model parameters are derived state times of approximately 600 and 300 seconds, respectively, to achieve the threshold injury states at 48.9°C. Thus, the current simulation is not expected to predict injury to the extent that would produce threshold injuries.

The data in Figure 5 contain information requisite to adapting existing hot water delivery standards to provide scald protection for children. As the insult temperature is reduced, the depth at which an equivalent injury is produced in children is increased. Interestingly, the relationship between these two parameters maps as a simple linear function. The temperature varies as an exponential function of depth (the error function in equation 2 is an exponential integral). The injury varies an exponential function of the inverse value of temperature (equation 4); thus, the linear relationship in Figure 5.

As progressively greater skin depths are chosen to identify equivalent scald conditions for children, the insult temperature is required to be lower. This effect can be understood in the context of the data shown in Figure 6, which presents the transient temperature histories at three pairs of matched depths in adult and child skin (324 and 450 μm, 432 and 600 μm, 540 and 750 μm). The adult simulation was at 48.9°C (120°F) and the child at 46.6°C (115.9°F). These two insult scenarios produce the identical levels of injury at the 432- and 600-μm depths. The temperature at the shallower location with the lower thermal stress (child) at the surface rises more quickly and at approximately 7 seconds is surpassed by the temperature at the deeper location with the higher surface thermal stress (adult). The earlier and later opposite sign differentials in these two profiles compensate to create the same magnitude of injury at 10 seconds. Although the differential is smaller and of lesser duration at the highest temperature range, the net accrual of injury is equal because the exponential dependence of equation 4 on temperature weighs higher temperatures more heavily. For more superficial depths, the two thermal plots cross at a shorter time and lower temperature, indicating that the child skin would require scalding at a higher temperature than 46.6°C to achieve an injury equal to adult skin at 48.9°C. Conversely, at a deeper skin position the surface temperature would have to be lower for child skin to allow adequate time for the thicker adult skin to respond at a higher temperature surface scald. The two thermal plots at the deepest locations do not cross before 10 seconds, with the consequence that the child burn injury level exceeds that of the adult.

The foregoing analysis demonstrates that, given the model assumptions exercised for this set of simulations, specification of a scald standard for children based on adapting the existing standards derived for burn criteria for adults depends directly on the selection of relative skin depth at which to evaluate injury. If the assumption is made that it is reasonable to allow the heat wave resulting from a surface scald to penetrate at least partially into the dermis, then at a depth of 450 to 600 μm, hot water temperature standards must be reduced 3 to 4°F to provide equivalent pro-

Figure 5. Scalding temperature and depth combinations that produce the same level of injury in the child skin simulation as does a 120°F scald at the equivalent fractional skin depth in the adult simulation.
tection to children as is afforded to adults at the present 120°F criterion.

Although a specific recommendation is made for reduction in domestic hot water temperature, it is appropriate to consider the levels of uncertainty involved in arriving at these numerical results. The primary sources of uncertainty derive from variations in the values of experimentally determined constitutive properties used in the calculations and variations among different members of population groups and at different locations on the body surface. For example, most measures of thermal conductivity of human tissues are presented with a standard deviation that ranges from approximately ±5 to 10%.10 Seidenari et al9 measured skin thickness for a group of 42 children at eight different sites on the body. The average thickness varied among the different sites by a factor of approximately two, and the standard deviations across the population at the different sites was on the order of ±15%. Thus, the differences in skin thickness across the body are greater that the differences in averages across a population of individuals, and the data for thermal conductivity are more accurately known that any of the foregoing. The consequence of this uncertainty of values input to the model is that it is impossible to explicitly predict the level of injury that will occur when there is a scald insult at a particular location on a specific individual. However, safety standards are not designed to provide that kind of information. Rather, they are intended to provide a guideline for ensuring the well being of a general population, and it is in that spirit that the current analysis was conducted. It is in this context that the existing hot water standards developed for adults can be recommended for alteration to account for a similar level of scald safety for children.

The recommendations forthcoming from this study are based on results obtained from adaptation of the basic burn mathematical model of Henriques and Moritz,1,2 which has been tested for more than a half century. The veracity of this mathematical model has been verified with reference to numerous complementary experimental data sets, including that of the original authors. Nonetheless, it is appropriate to question the level of confidence with which the recommendations from the present mathematical modeling study can be adopted for reformulating the safety standards for domestic hot water, especially because no experimental data are available to validate the results. Indeed, one clear use of the mathematical model outcomes could be to guide the design of subsequent experiments to efficiently measure the effect of decreased skin thickness of elevated susceptibility on scald injury. Confidence in the predictions from the mathematical burn model is most compromised when it is interpreted in terms of absolute levels of

Figure 6. Comparison of thermal histories that produce equal injuries after 10 seconds at a depth of 600 μm for 120°F (adults) and 432 μm for 115.6°F (children) at these plus the two bracketing sets of depths that were simulated. The equivalent depths for child skin are 72% that of an adult.
injury produced in response to defined thermal insult scenarios. A much greater confidence can be exercised when, as in the present case, the model is used to compare the relative levels of injury hazard for changing temperature and time of exposure and/or for variations in the skin thickness. The present study was designed to determine how a reduction in skin thickness would affect a safety standard that already exists, as defined in terms of maximum allowable domestic water temperature. Because the criteria used to evaluate the current model predictions are relative rather than absolute and because the basic model formulation has been applied successfully for more than 50 years by innumerable investigators around the world, the recommendations of this model provide an attractive alternative to the costs in resources, time, and experimental subjects, as well as the difficulty of designing an effective experimental protocol, to provide the requisite information for adjusting the set temperature for domestic hot water to accommodate the juvenile population.

CONCLUSIONS

The mathematical modeling analysis presented herein confirms quantitatively the increased susceptibility of children to scald injury owing to their thinner skin structure. The model comprises a basis for determining an appropriate adjustment to existing hot water scald safety standards to accommodate the needs of children against burn injury. The adaptation of the model for this purpose requires that a criterion for thermal damage be defined, specifically in terms of the skin depth at which the injury is identified. A reasonable guideline would be to adjust existing hot water standards downward by 3 to 4°F to provide for the safety of children in environments in which there is a danger of scald exposure. The explicit recommendation derived from this work is that the existing standard of a maximum temperature of 120°F for domestic hot water be reduced to 116°F to accommodate the increased need of children for protection owing to their thinner skin and therefore greater susceptibility to scald injury.

The results of this study are intended to serve as a guideline for standard setting organizations for making decisions on whether or not to modify existing hot water safety standards and, if so, by how much. Given the current paucity of information on the sensitivity of children to scald injury as compared with adults, the author has been requested by such organizations with responsibility for setting standards and codes to develop an analytical tool for this purpose. This work is intended to serve this stated function.

REFERENCES