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Review Article

Predictor of the depth of burn injuries: A time and temperature relationship review

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Abstract:
Introduction: Understanding the relationship between surface and water temperatures, length of exposure and depth of tissue injury is crucial. When providing expert opinion on potential non-accident injury cases, the duration of the injury and the temperature of any putative causative agent is always requested.
Methods: A systematic review was performed using the electronic databases Web of Science, PubMed, Ovid Medline, PsychInfo and Embase for papers published between 1945 to 2018. We looked exclusively at original papers investigating the relationship of time and temperature in the context of depth of burn injuries using Cochrane risk of bias tool to investigate methodology of each study design.
Results: A total of eight studies met the inclusion criteria. All studies were experimental models with only one comparative human-porcine model. Both contact and scald burns were investigated. There was overall agreement in all studies. The lowest temperature was 50°C that led to mid-dermal burns with a duration of exposure of ≥10 minutes. The highest temperature was 100°C that led to deep-partial thickness burns in 10 seconds.
Conclusion: This review has emphasised several factors that affect the severity of contact and scald burn injuries. It should be noted that the time-temperature relationship and threshold are dependent on one another.

Introduction

Burns affects people of all age groups and leads to scarring, disfigurement and even death [1]. It is a global health concern especially among young children, with the commonest burn injury being scalds [2]. To reduce the risk of burns, understanding the relationship between surface and water temperatures, length of exposure and depth of tissue injury is crucial. When providing expert opinion on potential non-accident injury cases, the duration of the injury and the temperature of any putative causative agent is always requested.

Having a standardized burn injury severity classification is highly important in clinical and research settings. However, clinical assessment to quantify burn depth through visual observation is challenging. Researchers have tried multiple ways to assess burn depth including MRI, ultrasonography, thermography, laser Doppler flowmetry, fluorescein fluorometry and vital dyes, with varying degrees of success [3-10].

Burn depth is a key determinant of prognosis in terms of morbidity and mortality [1,11]. Skin tissue thickness varies by body locations. The age of a person also affects skin thickness, with children having thinner skin than adults [12]. The exact site of the burn is important as the same temperature can have varying degrees of damage at different locations. Thicknesses of the epidermis, dermis, subcutaneous and muscle layers were described to be at an average of 0.08mm, 2.00mm, 10.00mm and 30.00mm respectively [13-15]. A collection of different studies [16-19] reporting on the various thickness of the tissue layer is tabulated on Table 1.

Table 1: Different tissue layers as described by the various studies

Authors	Tissue Layers	Body Location	Reported thickness(mm)
Southwood [16]	Epidermis	Face	0.052
		Back	0.065
	Dermis	Face	2.27
		Back	2.36
Whitton & Everall [17]	Epidermis	Cheek	0.039
		Upper arm	0.052
		Forearm	0.061
		Trunk	0.042
Sandby-Moller, Poulsen & Wulf [18]	Epidermis	Forearm	0.075
		Shoulder	0.081
		Buttock	0.097
Laurent et al. [19]	Epidermal-Dermal	Deltoid	2.09-2.13
		Waist	1.9-2.01
		Thigh	1.59-1.64

Many studies used animal models for obvious reasons. The wound healing mechanism in human and porcine skins are similar, and thus porcine skin was often used in burn studies [20]. A number of studies have created numerical simulations and physically realistic models to enable computational predictions of burn depth using well-established calculation methods, with the most widely used being the Arrhenius equation. Moritz and Henriques demonstrated an inverse relationship between thermal exposure intensity and duration required to produce a burn [21].

Time-temperature thresholds at which irreversible epidermal damage occurs is important to identify as it is used in the development of burn-prevention guidelines [22,23]. For example, the results from the works by Moritz and Henriques have been adopted in setting international hot water safety standards. [21,23]

The purpose of this paper is to present a systematic review of the evidence that relates surface temperature and duration of exposure and depth of burn injury. There is international importance of this area of research for societal benefits by improving public burn prevention guidelines, industrial standards and modifying devices to lessen the likelihood of getting burns [24,25]. Burn care teams may also use this data to improve local therapeutic regimens. In clinical settings, a lack of adequate burn history context remains a perpetuating problem. If detailed information about the conditions of the event was available, predicted burn severity would be very useful in guiding management and treatment decisions, and when to refer patients to burn centres. Data on predicted burn injury would also help experts ascertain whether the injury is consistent with the history given, especially in cases of suspected abuse. This data would also aid clinicians in giving medicolegal advice in inflicted burn injury cases, as the duration of exposure causing the burn could be fundamental in deciding the prosecution.

Methods

A comprehensive review of published papers was performed using the electronic databases Web of Science, PubMed, Ovid Medline, PsychInfo and Embase. Articles that were included in the review were published between 1945 to 2018. We looked exclusively at original papers investigating the relationship of time and temperature in the context of depth of burn injuries. An attrition diagram is as depicted on Figure 1.

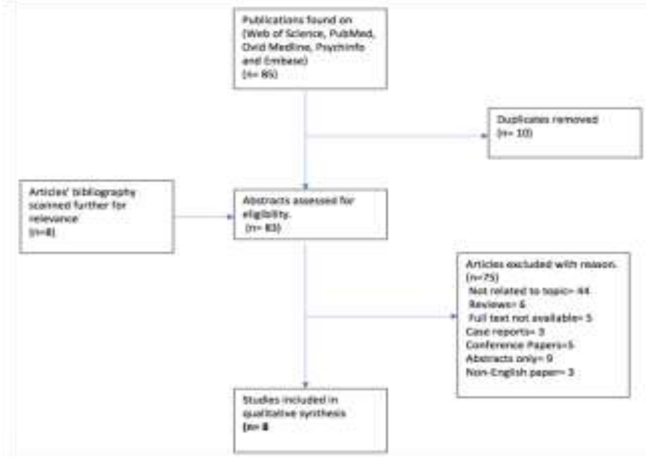

Figure 1: Attrition of studies

Keywords that were used were "temperature of water", depth of burn*", "scald* Injury*", "duration of exposure", "predictor of burn* severity". Depth of injury was categorised as being superficial partial thickness (SPT) burns, mid-dermal burns, deep-dermal burns and full thickness burns. Epidermis only involvement was not included in this review.

Data extraction

Inclusion criteria for the review were all original studies, human studies, animal models, computational numerical models, comparative, non-comparative studies and English language articles. Studies were evaluated for mechanism of burns (contact and hot water scalded only), temperature at which burns was inflicted, duration of exposure and depth of burn injury involved.

Exclusion criteria for the review were duplicates papers, review papers, case reports, conference papers, abstracts only, non-English papers and papers that are not of relevance to the purpose of this review.

Author names, year of study, burn model and outcomes measured and reported in the articles were recorded (Table 2).

			Outcomes measured (Yes/No)				
Author	**Year of Study**	**Burn model**	**Immersion injury**	**Spill/splash burns injury**	**Depth of Injury**	**Time to re-epithelisation**	**Cooling effect**
Andrews et al. [31]	2017	Porcine	Yes	Yes	Yes	Yes	No
Johnson et al. [13]	2011	Numerical	Yes	Yes	Yes	No	Yes
Mortiz & Henrique [23]	1947	Porcine & Human	Yes	No	Yes	No	No
Singer et al. [27]	2000	Porcine	No (Contact)	No	Yes	No	No

Abraham et al. [22]	2015	Numerical	Yes	No	Yes	No	Yes
Medina et al. [28]	2018	Murine	Yes	No	Yes	No	No
Cribbs, Luquette & Besner [29]	1998	Murine	Yes	No	Yes	Yes	Yes
Singh et al. [30]	2016	Porcine	No (Contact)	No	Yes	No	Yes

Table 2: Outcomes measured by each study reviewed

Study designs, sample size and sample wounds were also included in the review (Table 3).

							Domains			
Author	**Study design**	**Burn model**	**Sample size**	**Sample wounds**	**Clear inclusion criteria**	**Blinded outcome assessors**	**Attrition bias**	**Fundin g bias**	**Ethical approval**	**Risk of bias**
Andrews et al. [31]	Experimental	Porcine	24	115	Yes	Yes	No	No	Yes	Low
Johnson et al. [13]	Experimental	Numerical	16	16	Yes	Unclear	No	Unclear	Unclear	High
Mortiz & Henriques [23]	Comparative , Experimental	Porcine and Human	Pigs- 179, Human- 33	Pigs- 179, Human 33	Yes	Unclear	No	Unclear	Unclear	High
Singer et al. [27]	Experimental	Porcine	2	18	Yes	Yes	No	No	Unclear	Low
Abraham et al. [22]	Comparative , Experimental	Computational	unclear	unclear	Yes	Unclear	Unclear	Unclear	Unclear	High
Medina et al. [28]	Experimental	Murine	8-15 mice	unclear	Yes	No	No	No	Yes	Low
Cribbs, Luquette & Besner [29]	Experimental	Murine	47	47	Yes	Yes	No	Yes	Yes	Low
Singh et al. [30]	Experimental	Porcine	Unclear number of pigs	30	Yes	Yes	No	No	Yes	Low

Table 3: Cochrane risk of bias tool assessment

Due to heterogeneity of each study design, extensive statistical analysis was not possible for this review. However, a curved line of best fit with associated power model equation and goodness of fit measure (R^2) were calculated on the time and temperature scattered plot (Figure 2-5). A power model equation is a function with an equation in the form of $y= x^n$, where n is a fraction greater than 0.

Cochrane Risk of Bias Assessment

The Cochrane risk of bias tool was used to investigate the methodology of each study design with direct reference to Higgins & Green (2011)'s Cochrane Handbook for Systematic Reviews of Interventions [26]. Study design methodology was examined for inclusion criteria, blinding of assessors, attrition biasness, funding bias, ethical biasness and overall risk of bias. The risk of bias of the study was then classified as 'low' or 'high' (Table 3).

Results:

A total of eight studies [13,22,23,27-31] met the inclusion criteria of this study. With adherence to predefined inclusion and exclusion criteria, 10 duplicated studies were removed during preliminary assessment of article titles. Eight other studies that were obtained through scanning of relevant articles were included initially and investigated further for relevance. Forty-four papers unrelated to topic of review, six review papers, three case reports, five conference papers, nine abstract only studies and three non-English papers were removed. Five further studies with no extractable full text were removed as well. According to the risk of bias assessment, five studies had a low risk of bias and three other studies had a high risk of bias. The temperatures as well as their associated durations of exposure were tabulated (Table 4)

Table 4: Reported temperature and duration of exposure leading to depth of burns injury according to

published literatures

			Superficial-partial burns		Mid-dermal burns		Deep-partial burns		Full thickness	
Author	**Mechanism of Burn**	**Average burn size**	**Temperature (℃)**	**Duration of exposure**	**Temperature (℃)**	**Duration of exposure**	**Temperature (℃)**	**Duration of exposure**	**Temperature (℃)**	**Duration of exposure**
Andrews et al. [31]	Hot water scald	17.5 ± 0.7cm2	n/a	n/a	50	≥10 minutes	55	≥ 5 minutes	n/a	n/a
					55	2 minutes	60	1 minute		
					60	30 seconds	70	>15 seconds		
							85	5 seconds		
							90	5 seconds		
Johnson et al. [13]	Hot water scald	n/a	60	7.5-20 seconds	n/a	n/a	70	20 seconds	60	110 seconds
			70	7.5-10 seconds			80	10 seconds	70	110 seconds
			80	7.5 seconds			90	7.5-10 seconds	80	20-110 seconds
									90	20-100 seconds
Singer et al. [27]	Contact with heated aluminium rod	2.5 cm x 2.5 cm x 7.5 cm	60	10-30 seconds	70	20 seconds	70	30 seconds	70	30 seconds
			70	10 seconds	80	10-20 seconds	80	10-30seconds	90	30 seconds
					90	10 seconds	90	20 seconds	100	10-30 seconds
							100	10 seconds		
Abraham et al. [22]	Convection coefficient (Cooling)	n/a	n/a	n/a	n/a	n/a	63	38 seconds	n/a	n/a
							66	29 seconds		
							68	23 seconds		
							71	19 seconds		
							77	14 seconds		
							82	11 seconds		
							88	8.8 seconds		
							91	7.8 seconds		
							93	7.2 seconds		
	Convection Coefficient (No	n/a	n/a	n/a	n/a	n/a	63	31 seconds	n/a	n/a

	Cooling)									
							66	23 seconds		
							68	17 seconds		
							71	14 seconds		
							77	10 seconds		
							82	7.6 seconds		
							88	5.9 seconds		
							91	5 seconds		
							93	4.6 seconds		
Medina et al. [28]	Hot water scald	2x3cm	54	18 seconds	n/a	n/a	54	20 seconds	54	22 seconds
Cribbs, Luquette & Besner [29]	Hot water scald	2x3cm	n/a	n/a	n/a	n/a	n/a	n/a	60	45 seconds
Singh et al. [30]	Contact with heated aluminium rod	7.065 cm2	100	15 seconds	100	20 seconds	100	30 seconds	n/a	n/a

and discussed below. Time and temperature relationship scatter plots for SPT, mid-dermal, deep-dermal and full thickness burns were as depicted in Figures 2,3,4 and 5 respectively.

Temperature and Duration of exposure implicated in Superficial Partial-Thickness (SPT) burns

Based on the available literature on the thickness of the epidermal and dermal layer of various body parts, Johnson et al. [13] designed a numerical model to investigate the depth of injury of skin layers in relation to hot water temperature. It was considered that burn beyond 2mm was deemed as full thickness involvement and anything less than 1mm was recognised as superficial partial thickness. The experimental model of 16 burns reported that a water temperature of 60°C with a duration of 7.5 seconds to 20 seconds led to the development of superficial partial thickness (SPT) burn injury. A similar depth of scald injury was seen at 70°C and 80°C with a duration of exposure of 7.5-10 seconds and 7.5 seconds respectively.

Singer et al.'s [27] article discussed a two-way experimental model using six different temperatures for three durations of exposures of 10, 20 and 30 seconds on two porcine models. The study utilised a preheated aluminium rod in water temperatures of 50°C, 60°C, 70°C, 80°C, 90°C and 100°C on areas with an average of 2.5 cm by 2.5 cm by 7.5 cm in size. It was reported that at 60°C and a contact time of 10-30 seconds there was evidence of superficial partial thickness burns.

An experimental murine study carried out by Medina et al. [28] studied the bare area of the mouse that was directly in contact with the hot water without the presence of any air bubbles that may affect the set temperature of 54°C. A scoring system was developed from score 1 to 4 with 1 being limited to the epidermis, 2 extending through the epidermis but not beyond the base of the hair follicle, score 3 extending beyond the hair follicle but not through the dermis and score 4 through the dermis into the hypodermis. It was noted that at 54°C with a duration of 18 seconds, burn depth was categorised under score 2 which represented a superficial partial thickness burn.

Cribbs, Luquette & Besner's [29] murine model investigated burns inflicted on 47 mice and 47 wounds with an average size of 2 x 3cm. The study utilised temperature of 60°C for 45 seconds followed by cooling in water with a temperature of 4°C for another 45 seconds. It was reported that based on histological evaluation, 69% of the mice had superficial partial thickness burns with the other 11% having mixed partial thickness burns.

Singh et al. [30] developed an experimental model using contact from a customized aluminium rod to inflict injury at 100°C on the dorsum of pig skin. The article measured burn injury inflicted at different times from 5 seconds to 30 seconds using a constant force of 10 Newtons. It was noted that with a duration of exposure of 15 seconds, the depth of injury observed was at 1.21mm indicating superficial partial thickness burns.

Based on the SPT burn time-temperature scattered plot (Figure 2), the curved line of best fit equation was noted to be $y= 91.212x^{-0.128}$. The goodness of fit measure (R^2) was equalled to 0.1075 which meant that our data explained 10.75% of the variability of the response data from the mean.

Temperature and Duration of exposure implicated in Mid-dermal burns

Andrews et al. [31] in his experimental study on using hot water scald injuries to porcine models reported that 50°C, 55°C and 60°C of water with an exposure time of ≥10 minutes, two minutes and 30 seconds respectively can cause mid-dermal burns based on wound examinations at day 3 for immersion injury. It was also noted that spill/splash scalds injuries were evident at 75°C for 5 seconds with a temperature of 90°C being statistically significant ($p<0.05$) when compared to temperatures between 60-85°C.

Under H&E staining, it was noted that dermal parameters were becoming more evident in Singer et al.'s [27] study of contact burns on porcine models at when exposed to longer periods. Temperatures of 70°C, 80°C and 90°C, at durations of 20 seconds, 10-20 seconds and 10 seconds respectively recorded a depth of injury of between 1mm to 2mm when measured using an ocular micro-meter indicating mid-dermal involvement. Singh et al. [30] reported that the depth of injury was at 1.61mm when the porcine wound was inflicted with a contact burn of 100°C with a duration of 20 seconds.

Based on the mid-dermal burn time-temperature scattered plot (Figure 3), the curved line of best fit equation was noted to be $y= 118.66x^{-0.145}$. The goodness of fit measure (R^2) was equalled to 0.6851 which meant that our data explained 68.51% of the variability of the response data from the mean.

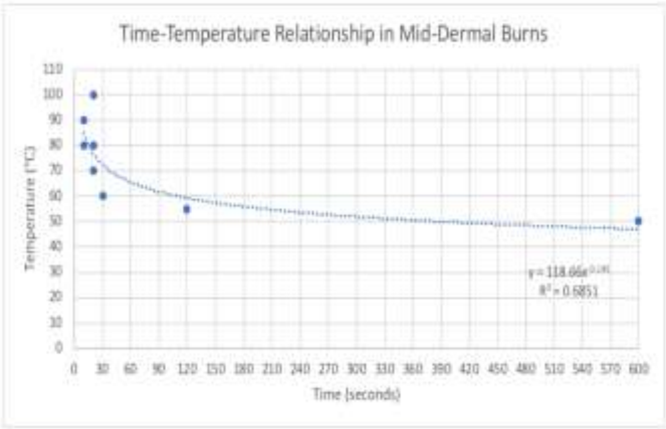

Figure 3: Time-temperature relationship in mid-dermal burns according to published literatures; Power model equation: y= y-axis, x= x-axis. R^2= Goodness of fit measure

Temperature and Duration of exposure implicated in Deep partial-thickness (DPT) burns

Further to the experimental study by Andrews et al. [31], the article reported on the time and temperature recordings that led to a deeper dermal injury. It was reported that up to 88% of the depth of the dermis was damaged after immersion in 55°C of hot water for 5 minutes. Three other immersion temperatures were tested in the report, 70°C, 85°C and 90°C which reportedly cause deep-dermal scalded injuries at ≥15 seconds, 5 seconds and 5 seconds respectively.

Johnson et al.'s [13] numerical model also reported that hot water exposure of 70°C, 80°C and 90°C for a duration of 20 seconds, 10 seconds as well as 7.5-10 seconds respectively produced deep-dermal scald injuries. At 70°C, a 20 second exposure yielded a burn 1.2 mm deep which was considered as partial thickness while exposure to a temperature of 80°C resulted in injury depth of between 1 mm to 2.3 mm. This was categorised as being deep-dermal.

Singer et al.'s [27] study further reported on a series of time and temperature leading to deep-dermal burns. It was reported that temperatures of 70°C, 80°C, 90°C and 100°C for a duration of 30 seconds, 10-30 seconds, 20 seconds and 10 seconds led to a significant dermal injury of depth of ≥ 2mm, indicating deep dermal involvement.

Abraham et al.'s [22] comparative experimental study used a numerical model which applied sophisticated convection coefficients to represent hot water scalding. It was noted that temperatures of 63°C, 66°C, 68°C and 71°C for a duration of 38 seconds, 29 seconds, 23 seconds and 19 seconds respectively with cooling led to deep-partial thickness burns. In addition to that, temperatures of 77°C, 82°C, 88°C, 91°C and 93°C for a duration of 14 seconds, 11 seconds, 8.8 seconds, 7.8 seconds and 7.2 seconds respectively with cooling, also led to evidence of deep partial-thickness burns. Its counterpart study reported a temperature of 63°C, 66°C, 68°C and 71°C with a duration of exposure of 31 seconds, 23 seconds, 17 seconds and 14 seconds without cooling led resulted in deep-partial thickness injuries. Additional temperatures were 77°C, 82°C, 88°C, 91°C and 93°C for a duration of 10 seconds, 7.6 seconds, 5.9 seconds, 5 seconds and 4.6 seconds respectively that led to deep partial-thickness burns. At a temperature of 100°C and 30 seconds exposure, Singh et al. [30] article reported a burn depth of 1.91mm indicating deep-partial thickness contact burn.

Based on the DPT burn time-temperature scattered plot (Figure 4), the line of best fit equation was noted to be $y= 113.23x^{-0.142}$. The goodness of fit measure (R^2) was equalled to 0.5206 which meant that our data explained 52.06% of the variability of the response data from the mean.

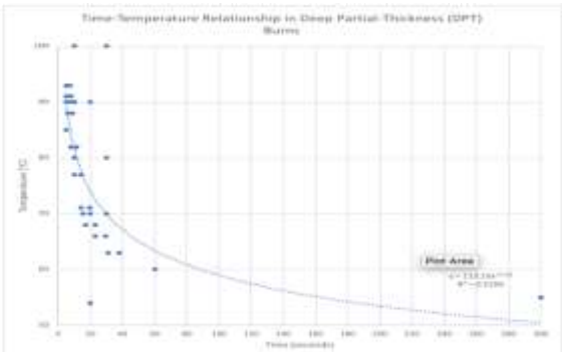

Figure 4: Time-temperature relationship in deep-partial burns according to published literatures; Power model equation: y= y-axis, x= x-axis. R^2= Goodness of fit measure

Temperature and Duration of exposure implicated in Full Thickness (FT) burn

Johnson et al.'s [13] experimental study found that water temperature of 60°C and an exposure duration of 110 seconds led to evidence of skin necrosis due to thermal injury beyond 2mm. In addition to that, water temperature of 70°C with a duration of exposure of 110s reported a depth of injury of approximately 4mm and 80°C, at 5.9mm which is far beyond the entire dermal layer. However, the relationship between temperature and depth of injury was evident as at 90°C, both 20 and 110 seconds resulted in full thickness injuries in their numerical models.

A depth of injury of ≥ 2.5mm was noted in Singer et al.'s [27] article for contact burns at temperatures of 70°C, 90°C and 100°C, at durations of 30 seconds, 30 seconds and 10-30 seconds respectively. Additionally, the murine study by Medina et al. [28] further reported that at 54°C paired with a duration of 22 seconds of exposure led to full thickness burns in majority of the mice used in the study.

Based on the FT burn time-temperature scattered plot (Figure 5), the line of best fit equation was noted to be $y= 102.54x^{-0.077}$. The goodness of fit measure (R^2) was equalled to 0.0923 which meant that our data explained 9.23% of the variability of the response data from the mean.

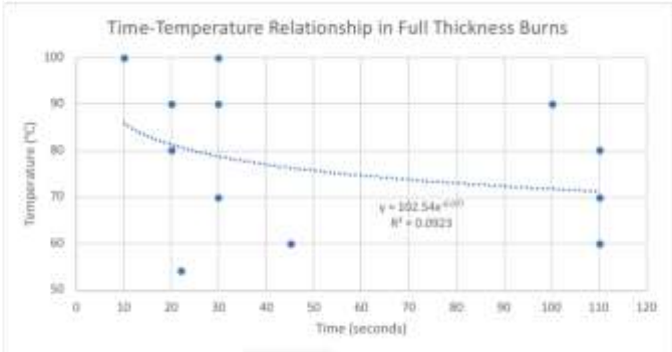

Figure 5: Time-temperature relationship in full thickness burns according to published literatures; Power model equation: y= y-axis, x= x-axis. R^2= Goodness of fit measure

Seminal study on time and temperature threshold

Using both human subjects and porcine models, Moritz and Henriques [23] carried out a comparative study investigating the time and temperature relationship (Table 5).

					2nd degree		3rd degree	
Author	**Mechanism of Burn**	**Sample size**	**Sample wounds**	**Average burn size**	**Temperature (℃)**	**Duration of exposure**	**Temperature (℃)**	**Duration of exposure**
Mortiz & Henriques [23]	Hot water scald	Pigs-179	Pigs- 179	Pigs- 25mm	70	2-180 seconds	70	2-180 seconds
					80	1-5 seconds	80	1-5 seconds
					90	1-5second	90	1-5second
		Human -33	Human-33	Human-7mm	44	6 hours	44	6 hours
					45	3 hours	45	3 hours
					47	25-45 minutes	47	25-45 minutes
					48	15-18 minutes	48	15-18 minutes
					49	9-15 minutes	49	9-15 minutes
					51	4-6minutes	51	4-6minutes
					53	1 minute	53	1 minute
					55	30 seconds	55	30 seconds
					60	5 seconds	60	5 seconds

Table 5: Reported seminal work by Moritz & Hendriques on the relationship of temperature of water and duration of exposure.

The temperatures that were used to study scald injuries ranged between 40°C and 100°C with a duration of exposure range of 1 second to 7 hours. 2nd and 3rd degree burns were classified under the same pathology as well in this article. In the porcine group consisting of 179 pigs, the majority of the findings were superficial 1st degree burns with temperatures of 70°C, 80°C and 90°C and a duration of exposure of 180 seconds, 1-5 seconds and 1-5 seconds respectively causing 2nd and 3rd degree burns.

In the human subjects group, 33 human subjects were involved with an average burn wound size of 7mm. It was noted that 2nd and 3rd degree burns were noted in a series of temperature between 44°C and 60°C. For hot water temperatures of 44°C, 45°C, 47°C, 48°C and 49°C, duration of exposure leading to 2nd and 3rd degree burns were at 6 hours, 3 hours, 25-45 minutes, 15-18 minutes and 9-15 minutes respectively. Furthermore, at temperature of 51°C, 53°C, 55°C and 60°C, duration of exposure was at 4-6 minutes, 1 minute, 30 seconds and 5 seconds respectively. Hence, it was concluded that the lowest temperature that could lead to scalded injuries was 44°C with time required to cause irreversible damage of the epidermal layer was at 6 hours.

Discussion

Duration and intensity of exposure Moritz and Henrique [23] investigated the importance of knowing the intensity and the duration of heat exposure in order to characterize the criticality of hyperthermia. By alluding to steady state thermal equilibrium effects, porcine data and conducting limited experiments on human subjects, they established time-temperature thresholds for the occurrence of cutaneous injury. Below 44°C, they noted a rapid decline in the rate at which injury occurred such that the time-temperature curve became asymptotic in the direction of the x-axis (time), i.e. thermal equilibrium was achieved by epidermal basal cells before irreversible injury occurred. They explained that since the hyperthermic level was within normal range for the tissue, physiological processes optimising thermal dissipation (inflow) was effective in counteracting thermal inflow which served to cause irreversible tissue injury. At these sub-threshold temperatures, the injuries sustained are considered to be so mild that no recognizable alteration in cell structure is apparent. These injuries require time to reverse which is related to the time required for their production [32].

As the exposure intensified, the time required to produce irreversible injury decreased such that above 51°C, the time-temperature curve became asymptotic in the direction of the y-axis (temperature). Above 51°C, the heat capacity of the epidermis is exceeded by the inflow of thermal energy such that the epidermal basal cells are deprived of the time required to institute physiological processes necessary for thermal outflow. With every degree rise in temperature, irreversible injury occurred exponentially.

Between 44°C-51°C, they observed a linear relationship between time and surface temperature in the production of burns such that with every degree rise, the rate of burning doubled.

Duration and frequency of exposure Moritz and Henrique [23] also investigated the effect of repeated sub-threshold exposures on the development of injury to the porcine epidermis and noted that longer exposure time accompanied by relatively short recovery periods resulted in irreversible trans-epidermal injury. The lower threshold was found to be three times of 3 minutes exposures at 49°C which resulted in irreversible injury unless a 24 minutes recovery period was allowed for. It is implied that longer and more intense exposures would require longer recovery periods to prevent irreversible tissue injury.

The results of this particular experiment using porcine model cannot be reliably extrapolated to that of human epidermal susceptibility to repeated sub-threshold exposures as it does not take into account the cooling evaporative effect from sweating on heat loss which porcine epidermis lack. Furthermore, the exposure sites were not histologically tested serially in equally divided time intervals so as to qualitatively determine exactly when irreversible injury sets in.

Effect of duration and intensity of exposure on depth of injury Histopathological assessments of burn injuries were performed by Singer et al. [27] who explored the temporal effects of various temperature exposures on the depth of dermal injuries due to burns. Johnson et al. [13], using numerical models also provided solid corroborative evidence that higher intensity exposure not only affected the superficial cutaneous layer, but also deeper ones. In both studies, a greater depth of cutaneous involvement was observed with higher intensity exposures with the superficial layers experiencing the highest increase in temperatures. Similarly, with longer duration exposures, a greater depth of cutaneous involvement was observed.

Johnson et al. [13] also found an inverse relationship between the degree of thermal injury and depth of cutaneous involvement. The degree of thermal injury sustained was highest towards the more superficial cutaneous layers with a diminishing degree of involvement of the deeper layers. With higher intensity exposures, the deeper cutaneous layers sustained a greater degree of thermal injury than was seen at lower intensities. The same was found to be true for the duration of exposure, with longer exposure durations resulting in a greater degree of thermal injury to the deeper tissue layers.

Interestingly, the deeper layers of the tissue bed continued experiencing increases in temperature, suggesting continual injury even after the removal of the heat source. These findings are qualitatively reinforced by a recent study of porcine models by Andrews et al. [31] using two clinically important parameters; depth of injury and time to reepithelialisation, both determined histologically. They demonstrated that with scald burn injuries of increasing temperatures and longer durations, a greater degree (%) of dermal damage was sustained. Shorter duration (spill/splash) scald injuries of sufficiently high temperatures resulted in deeper dermal damage. Longer duration (immersion) scald injuries too resulted in a significant amount of damage to the deeper dermal layers.

Through studies performed by Moritz [32] and Johnson et al. [13], it became clear that the duration and intensity of exposure affects the degree and depth of thermal injury. It is also known that the severity of thermal injury depends on the rate of heat transfer between the heat source and skin. This in turn depends upon the temperature of and duration of contact with the heat source, transfer coefficient, the specific heat and conductivity of the tissue as well as the thermal capacity of the agent.

There were a few limitations that were noted during this review. Most importantly, despite including murine models in our study, the results from these studies were deemed as not ideal due to the difference in skin thickness and the amount of skin in mice. However, we could expect that severity of injury would be increased with increased duration of exposure by correlating to these murine models. Furthermore, due to the paucity of available literature and the ethical issues of human studies, all study designs were included in the review; it can be assumed that the pathophysiology will not exactly reflect those of a real human subject. Additionally, older studies used different classifications for severity of burn injuries which made data interpretation difficult. Lastly, due to extreme values and heterogeneity of measured duration of exposure, the line of best fit and goodness of fit measure (R^2) may be skewed.

This review has emphasised several factors that can affect the severity of contact and scald burn injuries. It should be noted that the time and temperature relationship and threshold are dependent on one another. Most of the studies that were reviewed are unique to its own study design and methodology and should not be applied directly to a patient without thorough understanding and expert interpretation. It should also be noted that there were other published studies related to the duration of contact such as testing oximeter temperature, which have been performed in humans. However, these are not included in the study. Patient's pre- and post-burn factors plays an important and crucial role in the severity and outcome of the injuries.

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