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The Use of Thermal Imaging in Assessing Skin Temperature Following Cryotherapy: A Review

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5.1 Abstract

Background: Cryotherapy is used in various clinical and sporting settings to reduce odema, decrease nerve conduction velocity, decrease tissue metabolism and to facilitate recovery after exercise induced muscle damage. The basic premise of cryotherapy is to cool tissue temperature and various modalities of cryotherapy such as whole body cryotherapy, cold spray, cryotherapy cuffs, frozen peas, cold water immersion, ice and cold packs are currently being used to achieve this. However, despite its widespread use, little is known regarding the effectiveness of different cryotherapy modalities to reduce skin temperature. **Objectives:** To provide a synopsis of the use of thermal imaging as a method of assessing skin temperature following cryotherapy and to report the magnitude of skin temperature reductions associated with various modalities of cooling. **Design:** Structured narrative review. **Methods:** Three electronic databases were searched using keywords and MESH headings related to the use of thermal imaging in the assessment of skin temperature following cryotherapy. A hand-search of reference lists and relevant journals and text books complemented the electronic search. **Summary:** Nineteen studies met the inclusion criteria. A skin temperature reduction of 5-15°C, in accordance with the recent PRICE guidelines, were achieved using cold air, ice massage, crushed ice, cryotherapy cuffs, ice pack and cold water immersion. There is evidence supporting the use and effectiveness of thermal imaging in order to access skin temperature following the application of cryotherapy. **Conclusions:** Thermal imaging is a safe and non-invasive method of collecting skin temperature. Although further research is required, in terms of structuring specific guidelines and protocols, thermal imaging appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy. Currently there is ambiguity regarding the optimal skin temperature reductions in a medical or sporting setting. However, this review highlights the ability of several different modalities of cryotherapy to reduce skin temperature.

Key Words: PRICE, tissue temperature, cooling, infrared technology,

Highlights

► *Ambiguity exists regarding optimal skin temperature reductions after cryotherapy.* ► *This article reviews the use of thermal imaging to access skin temperature.* ► *Several techniques are available to assess skin temperature.* ► *Thermal imaging is a safe and non-invasive method of collecting skin temperature.* ► *Information is provided regarding a number of cooling modalities.*

5.2 Overview

Cryotherapy, the therapeutic use of cold, is applied in various clinical, rehabilitative and sporting settings to reduce odema, decrease tissue metabolism and provide analgesia (Knight, 1995). The basic premise of cryotherapy is to cool tissue temperature (Bleakley and Hopkins, 2010); various modalities such as whole body cryotherapy, cold water immersion, ice and cold packs are currently used to achieve this. Each of these cooling modalities has a different thermal property and therefore a different skin cooling potential (Bleakley and Hopkins, 2010). Skin temperature is a very important physical attribute and is used as a diagnostic parameter in various medical and sporting settings (Cholewka et al 2011). The magnitude of skin tissue cooling achieved in cryotherapy determines the treatment's ability to simultaneously achieve a meaningful analgesic effect and avoid adverse effects. Recent guidelines suggest that skin temperature reductions to less than 12°C are optimal for achieving analgesia (Bleakley et al., 2011, Bleakley and Hopkins, 2010). An optimal or safe lower limit for skin temperature is less clear however. Several instances of ice burn and even amputation are reported in the literature following prolonged or inappropriate cooling (Selfe et al., 2007). Other adverse events associated with excessive cooling include: nerve damage (Hoiness et al., 1998; Moeller et al., 1997), cold urticaria (Dover et al., 2004) and a compartment syndrome (Khajavi et al., 2004).

There are a significant number of cold modalities available to practitioners and athletes; knowledge of their cooling capacity is central to clinical safety and effectiveness.

Non-contact thermal imaging (TI) is a safe non-invasive method of collecting real time Skin Temperature (Tsk) data (Sherman et al 1996, Hildebrandt et al., 2010). Infrared TI has been used in medicine since the early 1960's (Ring and Ammer, 2000) and utilises the phenomenon that living and non-living objects all emit infrared radiation to some extent (Ammer, 2004). When the emissivity, the relative ability of a surface to emit energy by radiation, is known the intensity of infrared radiation can be used for calculation of the temperature of the emitting object (Ammer, 2004). The technology is a sophisticated way of receiving the electromagnetic radiation and converting it into electrical signals (Hildebrandt et al, 2010). These signals are finally displayed in gray shades or colours which represent temperature values (Hildebrandt et al, 2010). An example of an infrared thermal image of the anterior human body is displayed in figure 1. TI is widely used in medical settings such as cancer research (Head et a., 1995) and fever screening (Hewlett et al., 2011) to detect and locate thermal abnormalities characterized by an increase or decrease found at the skin surface (Hildebrandt et al, 2010). Selfe et al (2006) and Kennet et al (2007) have previously highlighted the effectiveness and the reliability of the use of TI to measure Tsk. The use of TI has recently become a popular method of assessing skin temperature following cryotherapy such as cold air cryotherapy, cold water immersion, ice cubes or cold packs in humans to assess skin temperature (Ammer, 2004). TI has been advocated in cryotherapy research primarily because it allows temperature data over the whole of the cooled area to be collected as opposed to a spot measurement obtained with a thermocouple (Hardaker et al, 2007).

Despite the significant number of original research studies and reviews assessing the effects of cryotherapy on Tsk, the optimal Tsk reductions in a clinical or sporting setting remains to be fully established (Bleakley et al, 2011). Consequently, answers to questions such as "what method of cryotherapy is the most effective in reducing skin temperature?", "is thermal imaging a reliable method of assessing skin temperature following cryotherapy?" and "what reduction in skin temperature is safe?" remain to be fully elucidated. Therefore the objectives of this current review were to determine a) the effectiveness of TI in assessing skin temperature following cryotherapy and b) the effect of different modalities on reducing skin temperature.

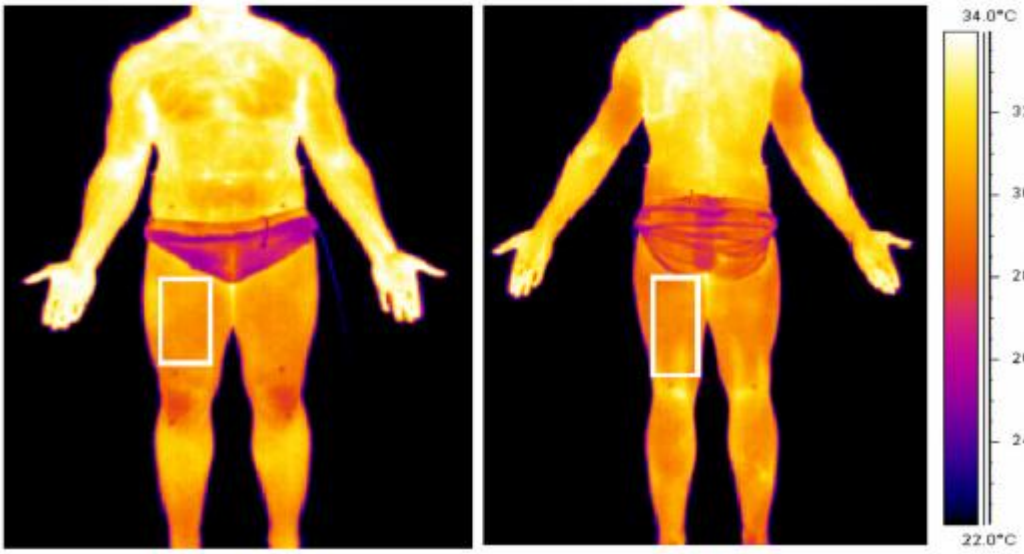

Fig. 1. An example of an anterior and posterior image of a subject in the anatomical position using infrared thermography. The inert markers, used to create regions of interest, are visible on the acromion, anterior superior iliac spine, posterior superior iliac spine, at the level of the olecranon, the popliteal fold, and 5 cm above and below the patella. The white frame, using the inert markers, creates a region of interest in the thigh.

5.2 Research Methods

We searched Medline, Pubmed and Science Direct search engines to identify studies that assessed skin temperature following a cryotherapy application using infrared thermal imaging. Keywords used included “thermal imaging and cryotherapy”, “thermal imaging and cooling”, “thermology and cryotherapy”, “skin temperature and cryotherapy”, “skin temperature and cooling” and “thermology and cooling”. No restrictions were made on study design or comparison group. Due to the advent of digital technology which has revolutionised the field of thermal imaging original papers published in the last decade were preferentially considered. The inclusion criteria for study selection were (1) the literature was written in English, (2) participants were human, (3) skin temperature assessed following a cryotherapy application, and (4) infrared thermal imaging was used to assess skin temperature. Articles were excluded if the title or abstract did not meet the inclusion criteria. Potentially relevant articles were also obtained by physically searching the bibliographies of included studies to identify any study that may have escaped the original search.

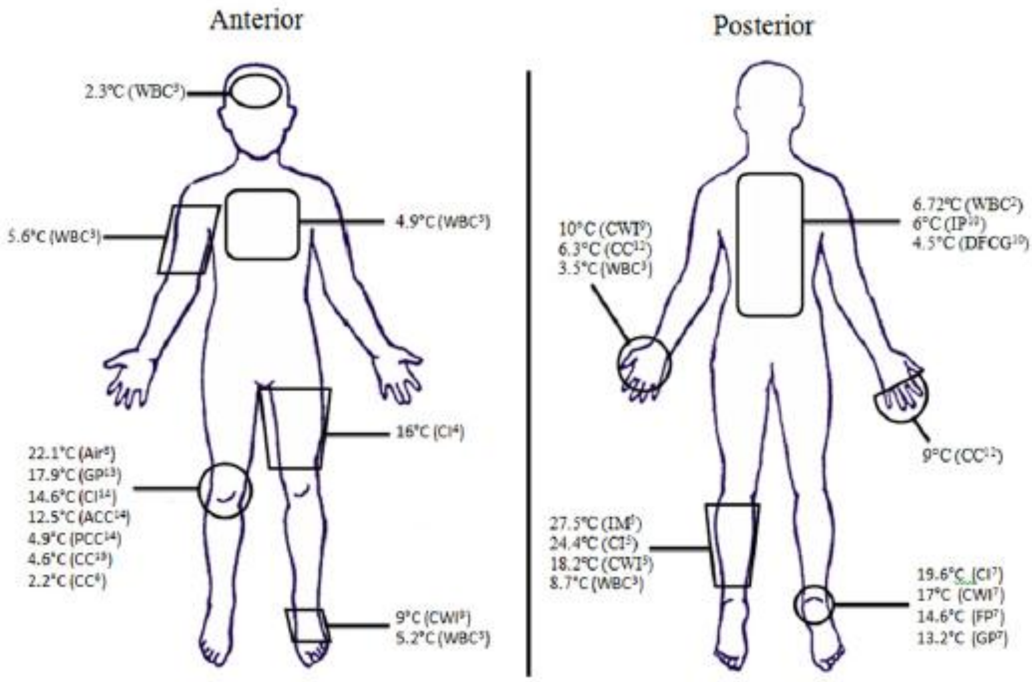

Fig. 2. Anterior and Posterior view of the maximum skin temperature reduction following the different cryotherapy modalities. Air=Localised Cold Air, (A)(P)CC=Analogue/Pump Cryo Cuff, IM=Ice massage, CI=Crushed Ice, CWI=Cold Water Immersion, DFCG=Deep Freeze Cooling Gel, FP¼Frozen Peas, GP=Gel Pack, WBC=Whole Body Cryotherapy (Cold Air). The superscripted numbers after the modality abbreviation indicate the relevant study where information was extracted. Cholewka et al. (2004)[1], Cholewka et al. (2006)[2], Cholewka et al. (in press)[3], Hardaker et al. (2007)[4], Herrara et al. (2010)[5], Karki et al. (2004)[6], Kennet et al. (2007)[7], Kim et al. (2002)[8], Rasmussen and Mercer (2004)[9], Ring et al. (2004a)[10], Ring et al. (2004b)[11], Robinson et al. (2010)[12], Selfe et al. (2007)[13], Selfe et al. (2009)[14], Selfe et al. (2010)[15].

Table 1

Studies assessing skin temperature following Cryotherapy using Thermal Imaging.

Author	Population N (M:F)	Treatment	Methodology	Immediate Effects	Duration of Effects
Cholewka et al. (2004)	a) N = 22 (17:5) LBP, Age = 47.1±10.1 b) N = 8 (7:1) Healthy, Age = 25±4.1	WBC (-120°C w/- 60°C) - t = N/A	- Back - Pre & Immediately Post Rx - T_{room} = n/a	a) 7 ºC[a] b) 4.35 ºC[a]	N/A
Cholewka et al. (2006)	a) N = 16 (10:6) LBP, Age = 25.6±3.9 b) N = 30 (23:7) Healthy, Age = 41.5±12	WBC (-120°C w/- 60°C) - t = 2 min (1st session), 3 min (2nd & 3rd session)	- T1/T2 to L5/S1 - Pre & Immediately Post Rx - T_{room} = 21.5 ± 1°C	N/A	N/A
Cholewka et al. (2010)	a) N = 18 (18:0) Anylosingspondylitis, Age = 50.6±8	WBC (-120°C w/- 60°C) - t = 3min	- T1/T2 to L5/S1 - Pre & Immediately Post Rx	a) 8.31ºC[a], b) 10.16ºC[a],	N/A

	b) N = 15 (13:2) Sciatica, Age = 44.7±7.6 c) N = 6 (6:0) Spondylarthosis, Age = 46±11.7 d) N =11 (11:0) Healthy, Age = 34±7.9		- d = 1.2-1.5m - T_{room} = 22.1 ± 1°C	c) 7.99ºC[a], d) 6.72ºC[a]	
Cholewka et al. (2011)	Healthy Age = 47.1±10.1 22 (17:5)	WBC (-120°C w/-60°C) - t = 3min	- Whole body by summation feet, shank, back, chest, arms, hands, head - Pre & Immediately Post Rx - d = 1.0-1.5m - T_{room} = 23 ± 1°C	5.8ºC	N/A
Gong et al. (2011)	Cervical Disk Herniation a) N = 10 (3:7) Control, Age = 35.1±5.8 b) N = 10 (2:8) WBC, Age = 34.8±4.2	WBC (-110°C w/-60°C) - t = 60sec (-60°C), 2.5min (-110°C), 30sec (-60°C)	- Upper Trapezius, Biceps Brachii, Triceps Brachii - Pre & Post Rx - T_{room} = 23-24°C	N/A The study aims only to compare treatments' effects on bilateral differences in	N/A

				T_{sk}	
Hardarker et al. (2007)	Healthy, Age = 27.8 9 (9:0)	CI - Thigh - t = 15 min	- Thigh - Pre & Immediately Post Rx (image/min for 40 mins) - T_{room} = 22°C	16ºC[b]	did not return to baseline T_{sk} after 40 min (remained 2-3ºC lower)
Herrera et al. (2011)	Healthy, Age = 20.5±1.9 36 (18:18)	CI, Ice massage CWI - Shank - t = 15 min	- Shank - Pre & Post Rx - d = as close as possible - T_{room} = 24 ± 0.08°C	CI = 24.43ºC[b], Ice massage = 27.6ºC[b], CWI = 18.23ºC[b]	N/A
Karki et al.	Healthy	CC	- Patella - Pre & Post Rx (1 image/min for	a) 1.0 ºC[a]	a) 2.2ºC[b] @ 16 min post Rx

(2004)	a) N = 19 (19:0), Age = 25.2 b) N = 20 (0:20), Age = 25.6	- Knee Joint - t = 3 min	25mins) - T_{room} = 20.2 - 23.3 °C	b) 1.1ºC[a]	b) 2ºC[b] @ 14 min post Rx - did not return to baseline T_{sk} after 25 min (remained 1-2ºC lower)
Kennet et al. (2007)	Healthy, Age = 24±4.6 9 (5:4)	CI, GP, FP, CWI - Ankle - t = 20 min	- Lateral aspect of the ankle - Pre & Immediately Post Rx (1 mage/min for 30 min), - d = 0.6m - T_{room} = 20.5±1.4°C	CI = 19.56±3.78 ºC[b], GP = 13.19±5.07 ºC[b], FP = 14.59±4.22 ºC[b], CWI = 16.99±2.76 ºC[b]	CI did not return to baseline T_{sk} after 35 min (remained 11.8ºC lower) GP did not return to baseline T_{sk} after 35 min (remained 5.2ºC lower) FP did not return to baseline T_{sk} after 35 min (remained 6.2ºC lower) CWI did not return to baseline T_{sk} after 35 min (remained 11ºC lower)

Kim et al. (2002)	Healthy, Age = 33.8±12.7 20 (15:5)	Cold Air - Knee Joint – lateral aspect - t = 5 min	- Knee - Pre Rx, During Rx (1 image/30 sec) & Post Rx (1 image/min for 10 min + 5 min for 120 min) - T_{room} = 26-28ºC	22.1ºC[b]	did not return to baseline after 120 min (remained 1-2ºC lower)
Klimek et al. (2011)	Age = 21.6±1.2 30 (15:15)	WBC (-110°C w/- 60°C) - t = 30sec (-60°C), 3min (-110°C)	-Anterior and Posterior thigh -Pre Rx & 15, 30, 45, 60, 75 and 90 min post treatment. - T_{room} = N/A	n/a	did not return to baseline after 90 min
Radmussen & Mercer (2004)	Healthy a) N = 12 (12:0) Young, Age = 24.8±3 b) N = 12 (12:0) Elderly, Age = 76.9±1 24 (24:0)	CWI - Hand and Foot - t = 2 min	- i) Hands and ii) Feet - Pre Rx & 2 image/min for 7 mins (first image taken 20s post), 1 image/min for following 8 mins, then 1 image/2mins - T_{room} = 26-28ºC	ai) = 10ºC[b], aii) = 9ºC[b], bi) = 10ºC[b], bii) = 8ºC[b]	ai) demonstrated and maintained hyperthermia after ~20 min (remained 1°C higher) aii) did not return to baseline T_{sk} after 60 min (remained ~1°C lower) bi) did not return to baseline T_{sk} after 60 min (remained ~ 1°C lower) bii) did not return to baseline T_{sk} after 60 min (remained

					~2°C lower)
Ring et al. (2004a)	Healthy N = 4 (4:0), Age = 26.5 N = 2 (0:2), Age = 32 & 26	DFCG & IP - Lumbar Spine - t = 10 min	- Lumbar Spine - Pre & Post Rx (1image/3min for 1hr) - d = 0.7m - T_{room} = 22°C	DFCG = 4.5ºC[b], IP = 6ºC[b]	DFCG did not return to baseline T_{sk} after 60 min (remained 4°C lower) IP demonstrated and maintained hyperthermia after 27 min (remained 2°C higher)
Ring et al. (2004b)	Healthy, Age = 20-45 years 6 (n/a)	DFCG1- direct application DFCG2 - rubbed in - L2/L4 - t = 60 min	- Lumbar Spine - Pre & Post Rx (1image/3min for 1hr) - T_{room} = 23±1°C	DFCG1 = 6ºC[b] DFCG2 = 6ºC[b]	DFCG1 did not return to baseline T_{sk} after 60 min (remained 6°C lower) DFCG2 did not return to baseline T_{sk} after 60 min (remained 4°C lower)
Robinson et al. (2010)	Carpel Tunnel Syndrome, Age = 54.7 14 (6:8)	CC - Hand and Wrist - t = 3 min	i) 2nd digit ii) 5th digit - Pre & Post Rx (1 image/min for 20 min) - T_{room} = 20.2 - 23.3°C	PreOp Hand-i = 6.2ºC[b] PreOp Hand-ii = 6.3ºC[b] PreOp Finger-i = 8.5ºC[b] PreOp Finger-ii	PreOp Hand-I demonstrated and maintained hyperthermia after ~15 min (remained ~0.2°C higher) PreOp Hand-ii demonstrated and maintained hyperthermia after ~15 min (remained ~0.2°C higher) PreOp Finger-i = did not

				= 9ºC[b]	return to baseline T_{sk} after 20 min (remained 1.5°C lower) PreOp Finger-ii = did not return to baseline T_{sk} after 20 min (remained 1°C lower)
Selfe et al. (2006)	Anterior Knee Pain 9 (n/a)	CC - Knee Joint - t = 3 min	- Knee - Pre & Post Rx (1 image/min for 20 min) - d = 0.8m - T_{room} = N/A	N/A	N/A
Selfe et al. (2007)	Sufferer of ice burn, Age = 43 1 (1:0)	GP - Patella - t = 20 min	- Knee - Pre & Post Rx (1 image/min for 25 min) - T_{room} = N/A	17.9°C[b]	did not return to baseline T_{sk} after 25 min but demonstrated a steep temperature gradient of 29.7°C
Selfe et al. (2009)	Healthy, Age = 29.6±9.3 11 (11:0)	CI, Analogue CC, Pump CC	- Knee - Pre & Immediately Post Rx - d = 0.91m	CI = 14.6±3.7°C[b], Analogue CC = 12.3±2.4°C[b], Pump CC =	N/A

		- Anterior Knee - t = 20 min	- T_{room} = 23.3±1.9°C	4.9±1.3°C[b]	
Selfe et al. (2010)	Anterior Knee pain, accentuated by cold a) N = 21 (7:14) Cold Knees, Age = 31.6±10.7 b) N = 37 (12:25) Not Cold Knees, Age = 30.1±13	CC - Knee Joint - t = 3m min	- Knee - Pre & Immediately Post Rx (1 image/min for 20 min) - T_{room}^{a}= 23.4±1.2°C - T_{room}^{b}= 24.7±2.7°C	a) 4.4C[a], b) 4.6C[b]	a) did not return to baseline T_{sk} after 20 min (remained 2.5°C lower) b) did not return to baseline T_{sk} after 20 min (remained 1.1°C lower)

[a] = $p<0.05$ vs pre-treatment, [b] = $p<0.05$ vs control group, (male : female), T_{sk} = skin temperature T_{room} = room temperature, Rx = treatment, t = time, n/a = not available, N/A = follow ups not measured beyond the immediate stages post Rx, T1/T2 = First/Second thoracic vertebra, L5/S1= fifth lumbar vertebra/first sacral vertebra, PreOp = pre operative, Air = Localised Cold Air, CC = Cryo Cuff, CI = Crushed Ice, CWI = Cold Water Immersion, DFCG = Deep Freeze Cooling Gel, FP = Frozen Peas, GP = Gel Pack, WBC = Whole Body Cryotherapy.

5.3 Magnitude and Duration of Skin Tissue Cooling

Physiotherapists, coaches, athletic trainers, and clinicians administer cryotherapy for numerous reasons, including the reduction of pain and swelling, to relieve muscle spasm, and to facilitate movement (Costello & Donnelly, 2011, Costello et al., epub). It has previously been suggested that cold application may relieve pain by numerous mechanisms including altered nerve conduction velocity (NCV), inhibition of nociceptors, a reduction in muscle spasm and/or a reduction in metabolic activity (Algafly & George, 2007, Airaksinen et al., 2003). The magnitude of tissue cooling following cryotherapy is therefore critically important as nerve conduction velocity is significantly and progressively reduced concomitantly with skin temperature following cold application (Algafly and George, 2007).

Of the 19 reviewed studies, which satisfied the inclusion criteria, 6 (Cholewka et al., 2004, Cholewka et al., 2006, Cholewka et al., 2010, Cholewka et al., 2011, Gong et al., 2011, Klimek et al., 2011) assessed skin temperature following Whole Body Cryotherapy (WBC), 5 utilised a cryotherapy cuff (Selfe et al., 2010, Selfe et al., 2006, Robinson et al., 2010, Karki et al., 2004, Selfe et al., 2009), 4 after crushed ice (Kennet et al., 2007, Hardarker et al., 2005, Herrera et al., 2011, Selfe et al., 2009), 4 after cold water (Kennet et al., 2007, Fushimi et al., 1996, Herrera et al., 2011, Radmussen and Mercer, 2004), 2 after gel pack (Kennet et al., 2007, Ring et al., 2004a,), 2 cooling gel (Ring et al., 2004a, Ring et al., 2004b), 2 ice massage (Ammer et all., 1996, Herrera et al., 2011), 1 after frozen peas (Kennet et al., 2007), while a further 1 after localised cold air (Kim et al., 2002). The duration of cooling ranged between 2 (Radmussen & Mercer, 2004) and 20 minutes (Selfe et al., 2007, Selfe et al., 2000, Kennett et al., 2007) with the average duration of cooling being 8.5 minutes. Five studies (Ring et al., 2004a, Ring et al, 2004b, Herrera et al 2011, Kennett et al 2007 and Selfe et al 2009) included a comparison of different cooling modalities, while no study compared different cooling durations. In addition to reporting skin temperature one study reported intra-muscular temperature (Hardaker et al., 2007) while no study reported core temperature.

The 19 eligible studies comprised of a total of 440 participants. Of these 273 were male, 152 women and the gender of 15 participants was not specified. The average sample size was 23 with the largest study based on 58 participants. A number of the reviewed studies used a healthy control group as a comparison to a patient population, with symptoms including lower back pain (Cholewka et al, 2004, Cholewka et al, 2006), anterior knee pain (Selfe et al, 2010), spondylarthosis (Cholewka et al, 2010), anylosing spondylitis (Cholewka et al, 2010) or sciatica (Cholewka et al, 2010). Three studies (Robins et al 2011, Selfe et al., 2006, Gong et al 2010) assessed only a patient population while the remaining focused on a healthy population. The purpose of three studies was to assess the effects of gender (Karki et al 2004, Klimek et al., 2011) and age (Radmussen & Mercer, 2004) on skin temperature following the application of cold. One study (Selfe et al 2007) was a case report on an individual who suffered from ice burn following an application of a gel pack for 20 minutes.

The temperature distribution over the body's surface provides useful information for many research and clinical applications. According to recent PRICE guidelines a reduction of 5-15 °C in tissue temperature, with the critical level of absolute skin temperature less than 12°C, is required to provide analgesia (Bleakley et al., 2011, Bleakley and Hopkins, 2010). However, larger reductions in skin temperature may cause injury (Bleakley and Hopkins, 2010). Figure 2 displays the maximum skin temperature reduction recorded by TI following the different cryotherapy modalities. Skin temperature of less than 12°C were achieved using ice massage, cold air, crushed ice, cryo cuff, ice pack and cold water immersion (Figure 2). WBC, cold air, gel packs, cryo cuff, cold water immersion, ice packs and frozen peas were all effective in reducing skin temperature by more than 5˚C at various locations. WBC did not reach the PRICE guidelines, with reductions of less than 5˚C at the hands, chest and forehead. However, it must be noted that during WBC in order to protect the face and extremities against the extreme cooling, subjects have to wear a mask, ear protection, socks, shoes and gloves and this attire may explain why these skin temperatures were not as significantly reduced as other regions. Similarly, a 10 minute application of Deep Freeze Cooling Gel and a 3 minute application of a cryo cuff were ineffective at reducing skin temperature in the back and knee respectively. Of the 19 included studies the lowest absolute skin temperature reported was 3.98°C, a mean reduction of 27.6 (±1.32) ˚C, following the application of ice massage (Herrera, 2011). However, it must be noted that Malone et al (1992) have previously stated that if the peripheral nerve is cooled below 10°C or if skin temperature is cooled to between 0 and 5 °C, cryotherapy can disturb function and cause motor/sensory loss.

In both a clinical and sporting setting, what happens to the temperature of the skin in the recovery period subsequent to the removal of the cold modality is of interest. In addition to reported skin temperature measurements immediately after the removal of the cryotherapy application, eleven of the reviewed studies reported follow up assessments of skin temperature. An interesting finding in all of these studies was that subjects' skin temperature, during follow up data collection, did not return to baseline levels after cryotherapy. In one study skin temperature still had not returned to baseline levels 120 minutes after exposure to cold air (Kim et al., 2002). In another study skin temperature 35 minutes after cold water immersion remained 11ºC lower than baseline (Kennett et al., 2007). Furthermore, Klimek and colleagues (2011) utilising a WBC protocol have reported significant reduction in thigh surface temperature 90 minutes following exposure in both males and females. It is common practise that cold is applied intermittently with periods of application and removal. The time period following removal of the cold modality should therefore be considered an important part of cryotherapy treatment sessions to achieve full therapeutic benefit (Hardaker et al., 2007). Clinicians must therefore be aware that during these cycles skin temperature may not have returned to baseline levels and need to be cognisant of the potential for cold induced injury.

As cryotherapy is often applied to treat muscle injuries it is also important to consider the relationship between skin and intramuscular temperature. The reporting of skin temperature has been criticised as being of limited value when observing the influence of cooling on subcutaneous tissues, with a number of studies suggesting there is no relationship between skin and muscle temperature. However, Hardaker et al. (2007) have reported that a strong negative quadratic relationship exists between intramuscular and skin temperature. These authors (Hardaker et al., 2007) report that the amount of heat an object can hold is directly proportional to it's volume and therefore the temperature of the muscle may be derived using the dispersion in the underlying tissue volume and the surface area of the skin that is being cooled. Interestingly as the skin temperature increases following the removal of the cryotherapy application intramuscular temperature decreases as the superficial tissues draw heat from the deeper tissues (Hardaker et al. 2007). Therefore, this is why the maximum reduction of muscle temperature is often recorded after the removal of cold, when the skin temperature has increased.

5.4 Technical Issues with the Methodology of Thermal Imaging following Cryotherapy

Hardware and analysis software produced by Flir Systems (Danderyd, Sweden) was the most commonly used in this review. In terms of the area thermographed the knee (Selfe et al., 2010, Selfe et al., 2009, Selfe et al., 2007, Kim et al., 2002, Karki et al., 2004) was the most common with five studies focusing on that joint. Other studies focused the ankle (Kennet et al), chest (Cholewka et al., 2011), thigh (Hardarker et al., 2005) and back (Cholewka et al., 2011, Cholewka et al., 2006, Cholewka et al., 2004) following a cryotherapy application. While Cholewka et al. (2011) reported skin temperature information from the head, chest, back, arms, tibias, hands and feet in order to calculate mean skin temperature following WBC.

The majority of the reviewed studies utilised the mean temperature from a Region of Interest (ROI) rather than spot measurements. In general, an area read-out should be used instead of spot measurements (Plassmann et al., 2006). In relation to data extraction the use of ROI has been advocated for a number of years (Kennet et al., 2007). A ROI, typically constructed as a quadrilateral on the post process computer software, is often applied to a pre-determined area of skin. Using skin or inert markers, attached to bony landmarks or anatomical locations, appear more reliable than using regions of interest determined from an image. The use of these inert markers, as used by (Selfe et al., 2006), means one has a clearly defined anatomic frame, through which a range of temperatures and images can be assessed consistently both within and between subjects.

Two further components to consider during thermal imaging is the distance the camera is from the area or region being thermographed, the room temperature of the laboratory where the TI took place (Ring and Ammer, 2000) and the emissivity factor. A limitation with the majority of the studies in this review was the failure to report either of these. The distance the area being thermographed is from the camera lens will affect the pixel resolution and has potential to alter the robustness of the data. It has also been suggested that a range of temperatures from 18°C to 25°C should be used during TI (Ring and Ammer, 2000). If the temperature range is below thermoneutral, the subject is likely to shiver, and above 25°C room temperature is likely to cause sweating, which will affect the reading (see table 1). In addition, during the analysis of skin temperature following the use of TI an emissivity of 0.97-0.98 has been recommended and used regularly in the literature (Steketee, 1973, Cholewka et al., 2011). However, a number of the reviewed studies have again failed to reports what emissivity factor was used during data collection. This is perturbing as the use of an incorrect emissivity would lead to an erroneous recoding of skin temperature.

5.5 Advantages and Limitations of Infrared Imaging Following Cryotherapy

A number of methods and devices of recoding skin temperature following the application of cryotherapy have been reported in the literature including thermocouples (Merrick et al, 2003), thermistors (Gregson et al., 2011), and other wireless sensors such as an iButton (Lichtenbelt, 2006). The greatest advantage of TI over these other methods of assessing skin temperature is the fact this it is non-invasive and portable. TI does not have to be in contact with the skin, an obvious advantage for measurement, especially in a clinical context. Skin thermistors and thermocouples often consist of a thin metallic foil which serves as a heat spreader backed by a foam insulation pad. This has the potential of creating a layer of insulation over the area of skin being assessed and therefore significantly degrades the accuracy of the measured temperature (Boetcher et al 2009). This artefact of testing, recording and reporting erroneous skin temperature data is therefore troublesome, especially if the temperature of the skin is being assessed during (or after) a cryotherapy treatment. The prime advantage that TI has over thermistors is the wealth of data that TI collects. Temperature variation over large areas of skin can be quantified quickly and accurately, with high resolution rendering each image the equivalent of hundreds or thousands of individual thermistor readings.

With the ability to create a ROI (see figure 1), using anatomical landmarks or inert markers as reference points, TI also allows an investigator to study a number of different (and larger) skin temperature sites. As a result the clinician can be confident that it is the actual temperature of the area of interest and is not confined to the spot measurements like the other techniques. In addition, of particular interest following cryotherapy or thermotherapy applications, TI has the capability to record the maximum, minimum and average skin temperature at any site. An ability to record the minimum skin temperature may be useful in future research on potential cold induced injury, which the minimum skin temperature rather than the average is pertinent. Furthermore, TI allows you to record, store and prints print images. This may be useful if recorded data needs to be retrospectively revisit, view or reanalysed.

In order to collect and report robust skin temperature data, clinicians and researchers alike face a number of challenges. In essence skin temperature data collection is inherently difficult to standardise due primarily to intrinsic and extrinsic factors. Intrinsic variables describe factors relating to the individual subject/patient and include caffeine/alcohol consumption, smoking, recent physical activity, circadian rhythm and gender. The influence of draughts, environmental temperature, heat sources (e.g. sun, radiators), acclimation period and clothing are some examples of extrinsic variables that may also have a significant effect on TI data. The majority of these variables can be relatively well controlled through effective protocol planning and communication with the subject prior to the commencement of TI but clinicians and researchers should be cognisant of these variables and endeavour to reduce their contribution. Although these intrinsic and extrinsic variables are not isolated to skin temperature assessments via TI, individually or collectively these factors could have a significant physiological effect and alter skin temperature recordings. Consequently, any protocol that included skin temperature assessment requires a great deal of planning and consistency.

One of the major limitations of TI is that to date, no standardised framework has been established (Ammer, 2008). Compared to other techniques that can assess skin temperature data, such as thermocouples or thermistors, TI can be expensive. Additionally, as moisture emits radiation, in order to use TI the skin surface must be completely dry. Any excess water on the skin (which is likely to occur following cold water immersion or any ice application) needs to be removed. Finally, compared to thermocouples or thermistors which could utilise a hand help battery operated devise, a computer with specialised software is usually required for TI and often a power source is required. This may reduce the effectiveness of TI as a technique of assessing skin temperature outside or in a field based study, as we have previously highlighted the potential effects varying ambient temperature or draughts may have on skin temperature.

5.6 Conclusion

Thermal imaging is a safe and non-invasive method of collecting skin temperature. Although further research is required, in terms of structuring specific guidelines and protocols, thermal imaging appears to be an accurate and reliable method of collecting skin temperature data following cryotherapy. Despite the ambiguity regarding optimal skin temperature reductions in a clinician or sporting setting, this review highlights the ability of several different modalities of cryotherapy, including WBC, cold air, gel packs, cryo cuff, cold water immersion, ice packs and frozen peas, to reduce skin temperature in accordance with the recent PRICE guidelines.

Conflict of Interest Statement

The authors declare they have not conflict of interest on the content of this paper.

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