TOPICAL REVIEW

Infrared thermal imaging in medicine

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This review describes the features of modern infrared imaging technology and the standardization protocols for thermal imaging in medicine. The technique essentially uses naturally emitted infrared radiation from the skin surface. Recent studies have investigated the influence of equipment and the methods of image recording. The credibility and acceptance of thermal imaging in medicine is subject to critical use of the technology and proper understanding of thermal physiology. Finally, we review established and evolving medical applications for thermal imaging, including inflammatory diseases, complex regional pain syndrome and Raynaud’s phenomenon. Recent interest in the potential applications for fever screening is described, and some other areas of medicine where some research papers have included thermal imaging as an assessment modality. In certain applications thermal imaging is shown to provide objective measurement of temperature changes that are clinically significant.

Keywords: infrared, skin temperature, inflammation, fever

Introduction

Quantitative thermal imaging was reviewed 21 years ago by Ring in this journal (Ring 1990). Considerable progress has been made over the last 20 years in the performance of infrared imaging equipment, standardization of technique and clinical protocols for thermal imaging. The physiological mechanisms of temperature distribution on the body surface are now better understood. This has resulted in more evidence for the diagnostic accuracy of thermal imaging in defined disorders. The value of temperature mapping as an outcome measure has also been established.
The thermal image

Infrared imagers

An infrared thermogram is an image of temperature distribution of the target. Although the second generation of infrared detectors was in use for military applications in the latter half of the 20th century (Rogalski 2011), thermal imagers used in medicine were almost exclusively scanning detector units with one to ten elements. Average speed rates were 1 to 16 frames per second, temperature resolution was 0.5 °C and spatial resolution was about 5 mm at a target size of 50 cm² (Ring 1984). However, high resolution in temperature (better than 0.1 °C) and spatial resolution (less than 0.1 mm) at frame rates of 25 per second were available in special designed equipment (Alderson and Ring 1995). In addition, all detectors needed a cooling mechanism such as nitrogen, argon gas or a sterling cooler. Focal plane array infrared cameras became common in the 1990s, and this new equipment provided improved spatial resolution necessary to resolve thermal patterns caused by superficial skin vessels (Ring and Dicks 1999) (figures 1, 2). Smaller camera units and the use of microbolometers lead to higher mobility and imaging of objects in the perpendicular view i.e. with the camera mounted in the vertical position, which can now be used with modern uncooled equipment. However for
Figure 3. (A) Chronic inflammation of the forefoot following a sports injury; (B) rheumatoid arthritis of one knee (left of the image).

Figure 4. The effects of stress on hand thermograms, (A) 10 min full normal recovery from 1 min immersion in water at 20 °C, (B) in a patient with Raynaud’s phenomenon after 10 min. (C), (D) Examples of hand arm vibration injury to certain fingers, showing delayed recovery after vibration and thermal stress have been applied. The affected fingers are cooler.

very high sensitivity detectors such as the quantum well infrared photodetector, cooling is still necessary.

The non-uniformity value is a measure for the variation in temperature recorded by each measuring point within the focal plane array. The defined threshold of 0.04% can only be achieved by correcting the raw data with software, meaning that inbuilt computing is necessary to achieve accurate temperature measurements.

Standardization

Within recent years some progress has been made in improved standardization protocols. The International Standards Organization has published two new documents defining the use of a thermal imaging camera for fever screening. The first in September 2008 (IEC 2008) describes the essential design and performance characteristics of a radiometric infrared camera for screening, where differences on the face can be little more than 1 °C, and the second in March 2009 defines the recommended mode of deployment including the testing of the system and the training of its users (ISO 2009).

There is now increased awareness of the potential measurement errors caused by the imaging system itself. A series of simple tests have now been proposed for regular quality assurance for thermal imaging in medicine (Plasman et al 2006). The use of external reference temperature sources is an important recommendation for regular calibration checks, especially with the modern uncooled detector-based cameras (Simpson et al 2008).

Today, digital images and image processing have become the standard, with many different colour palettes applied by different users. For example in engineering applications a colour
palette called ‘iron’ is used where yellow is hotter than red, and white is hotter than yellow, as found when iron is heated in a furnace. In medicine, where the temperature range is more limited (typically 10 °C) a ‘rainbow’ palette is preferred, with red as hot and blue/black as cold. These colour scales may also be linear or logarithmic in distribution, and in some software packages, the user can generate his own colour scale for a specific application if required. In general, the temperature colour scale used at the time of image capture should be displayed alongside the final image. Without this, the image is poorly defined, since the range and level of temperatures are essential to the full information provided in the thermogram. These issues are frequently defined in any standardization protocol, since they are essential elements for the comparison of thermograms to indicate change. They are also essential in evidential material for forensic and legal issues (ISO 2009).

Over the last 20 years, there has been a growing interest in standardization of procedures for clinical protocols including patient preparation, body positions for image recording and evaluation of thermal imaging. Previous guidelines for thermal imaging in medicine have included specific patient positioning to obtain the views required for medical thermography. Reference temperature values of healthy subjects have yet to be systematically obtained. There are some data that the mean temperature varies little between regions of the right and left side of the body, but absolute temperature values have seldom been reported. Some of these data will become available from the ‘reference atlas for clinical thermography’ project which began at the University of Glamorgan in 2001. A total of 24 body positions and 90 regions of interest have been defined in order to construct a clinical database of reference thermograms (Ammer 2008a). The improved reproducibility of body positions and location of regions of interest has been shown to have a marked influence on both the accuracy and precision of temperature measurements obtained from thermal images.

The influence of regions of interest of different shape and size of diagnostic accuracy of thermal imaging for thoracic outlet syndrome has been reported. Also the thermographic diagnosis of Raynaud’s phenomenon has been shown to be dependent on the definition and positioning of regions of interest (Ammer 2008b). A systematic review on the cold challenge test for provocation of vasospastic reactions of finger blood vessels found a wide variation in water temperature of the immersion bath and also of duration of immersion. More than 20 different methods for evaluation of hand temperatures have been reported (Ammer 2009). However, immersion in water of 20 °C for 1 min and use of a temperature gradient combining the temperature gradient from the fingertip to the dorsum of the hand prior and 20 min after the cold challenge has evolved as a proposed standard from the systematic review (Ammer 2009).

Applications of thermal imaging in medicine

The study of temperature has widespread applications across science and industry.

Thermal imaging offers the great advantage of real time two-dimensional temperature measurement. With modern technology, a single image may contain several thousands of temperature points, recorded in a fraction of a second.

The human body is homeothermic, i.e. self-generating and regulating the essential levels of temperature for survival. As humans we increase our ‘comfort’ by added clothing for insulation in winter, or decreasing clothing levels in the summer. The body core is relatively stable in temperature, but the shell of the body (the surface tissues mainly the skin) forms part of the regulatory process. Human skin behaves as an almost blackbody with an emissivity of 0.96–0.98. An American physiologist J D Hardy showed in 1934, that the emission of human
skin peaks at 9–12 μm. However detectors operating at 2–5 μm and bolometer systems operating up to 15 μm have all proved to be equally successful in medical applications.

The association between human body temperature and disease is almost as old as medicine itself. For generations physicians had to rely on the clinical thermometer, a simple maximum thermometer for a narrow range of body temperature close to 37 °C. The level of temperature was measured in a cavity such as the mouth, and principally used for the detection of fever.

Thermal imaging has been used mainly for research over the last 50 years. It has been used to study a number of diseases where skin temperature can reflect the presence of inflammation in underlying tissues, or where blood flow is increased or decreased due to a clinical abnormality. In principle, thermal imaging can be applied in medicine either as a diagnostic test or as outcome measure for clinical trials.

**Inflammatory arthritis**

From early times physicians have used the cardinal signs of inflammation, i.e. pain, swelling, heat, redness and loss of function. When a joint is acutely inflamed, the increase in heat can be readily detected by touch. However, subtle changes in joint surface temperature occur, and increase and decrease in temperature can have a direct expression of reduction or exacerbation of inflammation. This means that changes due to treatment, whether pharmaceutical, physical or surgical, can be objectively measured (See figure 3).

Studies were conducted throughout the 1960s to establish the best analogues of corticosteroids and their effective dose. Work by Collins and Cosh in 1970 and Ring and Collins in 1970 showed that the surface temperature of an arthritic joint was related to the intra-articular joint, and to other biochemical markers of inflammation obtained from the exudate. In a series of experiments with different analogues of prednisolone (all cortico-steroids), the temperature was measured by thermal imaging in groups of patients, and used to objectively determine the duration and degree of reduction in inflammation (Esselinckx et al 1978, Bird et al 1979).

A number of new non-steroid anti-inflammatory agents were introduced into rheumatology in the 1970s and 1980s. Infrared imaging was also shown to be a powerful tool for the clinical testing of these drugs, using temperature changes in the affected joints as an objective marker. The technique had been successfully used on animal models of inflammation, and effectively showed that optimal dose response curves could be obtained from temperature changes at the experimental animal joints. The process with human patients suffering from acute rheumatoid arthritis was adapted, to include a washout period from previous medication. The compound used by all the pharmaceutical companies was paracetamol. A study by Bacon et al (1977) found that small joints such as fingers and metacarpal joints increased in temperature quite rapidly while paracetamol (analgesic) treatment was given, even if pain was still suppressed. Larger joints, such as knees and ankles required more than 1 week off active anti-inflammatory treatment to register the same effect. Nevertheless, the commonly accepted protocol was to switch from analgesic to the new test anti-inflammatory treatment after 1 week of washout therapy. In every case if the dose was ineffective the joint temperature was not reduced. At an effective dose, a fall in temperature was observed, first in the small joints, then later in the larger joints. Statistical studies were able to show an objective decrease in joint temperature by infrared imaging as a result of a new and successful treatment. However, temperature measurements over joints have not generally been considered for inclusion in core sets of outcome measurements for the assessment of response to newer biological agents for inflammatory arthritis. Recently, a pilot study from the United States found a high coincidence between high temperature and swelling of finger joints detected by three-dimensional images. The authors created a heat distribution index which had a diagnostic sensitivity of 67% and a specificity of 100% for arthritic swelling (Spalding et al 2008).
Osteoarthritis

Varju et al compared thermograms with radiographs from patients with hand osteoarthritis (Varju et al 2004). They reported increased temperatures associated with even slight degenerative changes (Kellgren–Lawrence grade 1) and low temperatures in more severe disease (Kellgren–Lawrence grades 2–4). However, patient age in the different grades of severity of osteoarthritis has not been reported, and the decrease of surface temperature over more severely affected joints could have been caused by concomitant diseases. For instance, Ammer reported lower temperatures of affected fingers in patients with Raynaud’s phenomenon, carpal tunnel syndrome or thoracic outlet syndrome (Ammer et al 2002). The wide range of finger joint temperature between 21.42 and 37.17 °C recorded at an ambient temperature of 21 °C (Varju et al 2004) may question the accuracy of the temperature measurement.

Based on the available literature, Selfe et al considered a side-to-side temperature difference of the anterior knee greater than 0.5 °C to be clinically important (Selfe et al 2008). Good reproducibility was reported for the mean, minimum and maximum temperature readings of the anterior knee on two consecutive days (Hildebrandt and Raschner 2009).

There have been studies in arthritis to compare radiographs and thermal images published from Japan (Warashina et al 2002) and recently from the United States (Denoble et al 2010). Both papers found a good correlation between increased temperature and more severe changes in radiographs from osteoarthritic knees. Collins and Ring reported earlier in 1974 higher temperatures found in patients with osteoarthritis of knees or ankle joints than in normal subjects (Collins et al 1974), but did not relate the temperature with the severity of degenerative joint disease.

Thermal imaging was used to monitor patients after knee endoprosthesis (Lambiris and Stoboy 1981, Mayr 1995, Glehr et al 2011, Romano et al 2011). Lambiris et al claimed a high increase of temperature in case of infection after knee surgery and that the temporary elevation of temperatures returns to normal values within 4 to 6 weeks (Lambiris and Stoboy 1981). Mayr reported that the time to achieve normal temperatures after knee surgery is at minimum 120 days, but thermal symmetry over the knee joints was not achieved even after 10 months in some patients (Mayr 1995). A study from Italy observed identical anterior knee temperature 90 days after total knee replacement (Glehr et al 2011). Romano et al investigated patients with anterior knee pain which had developed after implantation of an artificial knee joint 1–9 years previously (Romano et al 2011). The study participants had to walk 3 km prior to acclimatization to a room temperature of 20 °C for 20 min. On the thermal image a reference temperature over the patella was compared with the temperature readings at the painful knee site. Mean temperature differences between painful and non-painful sites ranged between 0.8 and 0.9 °C. The authors claimed a diagnostic sensitivity of 100% and a specificity of 91.7% for painful sites at cut-off point of 0.1 °C temperature difference between painful and non-painful sites.

Soft tissue rheumatism

Muscle spasm and injury. Muscle action is the most important source of increased metabolic heat. Therefore, contracting muscles contribute to the temperature distribution at the body’s surface of athletes (Tauchmannova et al 1993, Smith et al 1986). Pathological conditions such as muscle spasms or myofascial trigger points may become visible as regions of increased temperature (Fischer and Chang 1986). An anatomic study from Israel proposed that in the case of the levator scapulae muscle, the frequently seen hot spot on thermograms of the tender
tendon insertion on the medial angle of the scapula could be caused by an inflamed bursae and not by a taut band of muscle fibres (Menachem et al. 1993).

Acute muscle injuries may also be recognized by areas of increased temperature (Schmitt and Guillot 1984) due to inflammation in the early state of trauma. However, long lasting injuries and also scars appear as hypothermic areas caused by reduced muscle contraction, and therefore reduced heat production. Similar areas of decreased temperature have been found adjacent to peripheral joints with reduced range of motion due to inflammation or pain (Ammer 1995a). Reduced skin temperatures have also been related to osteoarthritis of the hip (Kanie 1995) or to the frozen shoulder (Vecchio et al. 1992, Ammer et al. 1998). The impact of muscle weakness on hypothermia in patients suffering from paresis has been discussed elsewhere (Hobbins and Ammer 1996).

**Enthesiopathies.** Muscle overuse or repetitive strain may lead to painful tendon insertions, or where the tendons are shielded by the tendon sheath or adjacent to bursae, with painful swelling. It has been shown that tendovaginitis in the hand was successfully diagnosed by skin temperature measurement (Graber 1980). The acute bursitis at the tip of the elbow was also detected through an intense hot spot adjacent to the olecranon (Mayr 1997).

**Tennis elbow.** Painful muscle insertion of the extensor muscles at the elbow is associated with hot areas on a thermogram (Binder et al. 1983). Thermal imaging can detect persistent tendon insertion problems of the elbow region in a similar way as isotope bone scanning (Thomas and Savage 1989). Hot spots at the elbow have also been described as having a high association with a low threshold for pain on pressure (Ammer 1995b). Such hot areas have been successfully used as outcome measure for monitoring treatment (Devereaux et al. 1985, Meknas et al. 2008). In patients suffering from fibromyalgia, bilateral hot spots at the elbows is a common finding (Ammer et al. 1995).

**Fibromyalgia.** There are two terms used by physicians in the examination of muscular pain: tender points (important for the diagnosis of fibromyalgia) and trigger points (main feature of the myofascial pain syndrome). Tender points and trigger points may give a similar image on the thermogram. If this is true, patients suffering from fibromyalgia may present with a high number of hot spots in typical regions of the body. A study from Italy did not find different patterns of heat distribution in patients suffering from fibromyalgia and patients with osteoarthritis of the spine (Biasi et al. 1994). However, they reported a correspondence of non-specific hyperthermic patterns with painful muscle areas in both groups of patients. In an Austrian study, thermographic investigations in fibromyalgia revealed a diagnostic accuracy of 60% of hot spots for tender points (Ammer et al. 1995). The number of hot spots found was greatest in fibromyalgia patients and least in healthy subjects. It was therefore concluded that more than seven hot spots could be predictive for tenderness in 11 or more of 18 specific sites (Ammer 2008c). Based on the count of hot spots, 74.2% of 252 subjects (161 fibromyalgia, 71 with widespread pain, but less than 11 tender sites out of 18, and 20 healthy controls) were correctly diagnosed. However, the intra- and inter-observer reproducibility of hot spot count is poor (Ammer and Engelbert 2009). Software assisted identification of hot or cold spots based on the angular distribution around a thermal irregularity (Anbar 1990) might improve reproducibility.

**Complex regional pain syndrome**

A temperature difference between the affected and the non-affected limb equal or greater than 1 °C is one of the diagnostic criteria of the complex regional pain syndrome (CRPS) (Wilson
et al 1996). Ammer conducted a study in patients after radius fracture treated conservatively with a plaster cast (Ammer 1991a). Thermal images were recorded within 2 h after plaster removal and 1 week later. After the second thermogram an x-ray image of both hands was taken. The mean temperature difference between the affected and unaffected hand was 0.6 °C after plaster removal and 0.63 °C 1 week later. In some 50% of 41 radiographs slight bone changes suspected of algodystropy were found. It was also shown that the temperature difference decrease during successful therapeutic intervention and the temperature change was paralleled by reduction of pain and swelling and the resolution of radiological changes (Ammer 1991b).

Disturbances in the vascular adaptation mechanism and delayed response to temperature stimuli have been observed in patients suffering from CRPS (Cooke et al 1989, Herrick et al 1994). These alterations were interpreted as being caused by abnormalities of the autonomic nerve system. It was suggested that a cold challenge on the contralateral side of the injured limb for prediction and early diagnosis of CRPS could be used. Gulevich et al (1997) and Conwell et al (2010) confirmed the high diagnostic sensitivity and specificity of cold challenge for the CRPS. Wasner et al achieved similar results by whole body cooling or whole body warming (Wasner et al 2002). Recently a Dutch study found that the asymmetry factor which was based on histograms of temperatures from the affected and non-affected hand had the highest diagnostic power for CRPS; however the difference in mean temperatures did not discriminate between disease and health (Huygen et al 2004). McCabe et al investigating the use of mirror visual feedback as a means of treating type I CRPS found that patients who were successfully treated in this way during the early stages of the disease did show a return to thermal symmetry between the affected and non-affected limb, which was objectively measured by thermography. The thermal changes were associated with the relief of symptoms (McCabe et al 2003).

Peripheral circulation

In some circulatory disturbances, such as Raynaud’s phenomenon, or hand arm vibration syndrome, damage to small blood vessels from exposure to vibrating machinery and the effect of local blood circulation on skin temperature can be assessed by thermal imaging. This is found after exposure of the hands to a temperature stimulus or contact with a vibrating surface at a known frequency. Most commonly, a number of studies have reported the value of the thermal challenge test, particularly for quantifying the ‘vasospastic’ reaction found in Raynaud’s phenomenon (Ammer 2009). After a baseline thermogram of both hands (usually of the dorsal surfaces) the hands are protected by plastic gloves and immersed in a water bath (typically 18–20 °C) for 1 min. The thermal recovery is then monitored. In normal healthy subjects this can lead to a reactive hyperaemia of the fingers, while in Raynaud’s sufferers there is a slow protracted recovery of more than 15 min to baseline. This test has been applied in many different studies and trials of vasodilator treatments. In most cases, some improvements can be measured, but ultimately normal recovery is rarely achieved, even when there is an improvement in clinical symptoms.

A recent study by Vardasca has shown that hand arm vibration syndrome can be objectively measured by a combination of a vibration stress and a thermal stress to the hands (Vardasca 2010). Since this remains an important issue in occupational health, it is promising that this technique may improve the diagnostic discrimination in those industrial workers who are affected (See figure 4).

In all medical applications, the technique can only provide an image of skin temperature distribution; it does not provide data at a specific depth inside the body, as is common in other
imaging methods. However, thermal imaging is non-invasive and objective, and therefore safe and harmless.

The small size and weight of the modern cameras are similar to a domestic camcorder. This means that they can now be employed in the operating theatre, and have been used successfully to monitor the surgical procedures in open-heart surgery. Another evolving application of thermal imaging is the identification and localization of nutrient vessels in free perforator flap surgery. Based on work from Finland (Zetterman et al 1999) and Japan (Chijiwa et al 2000), a group from Norway had clearly shown that the design of deep inferior epigastric artery perforator flaps which are used for breast reconstruction can be based on dynamic infrared thermal imaging for pre-surgical selection of the vessel (De Weerd et al 2009b). In the abdominal region, blood vessels in the subcutaneous tissue are connected with the vascular system of abdominal muscles by perforating vessels which terminate in the subdermal layer. These vessels transport warm blood from the deep tissue to the surface of the body and are easily detected on a thermal image after the skin has been cooled by forced convection. In the rewarming phase the perforators appear as a rapidly growing hot spot on the skin. Infrared imaging is also a valuable tool for intraoperative (De Weerd et al 2006) and postoperative (De Weerd et al 2009a) monitoring in flap surgery.

**Fever screening**

Currently, there is interest in the use of thermal imaging for fever screening. Following the SARS (severe acute respiratory syndrome) outbreak in South East Asia, increasing use of thermal imaging had been made to screen travelling passengers at the time of pandemic fever. For this reason The International Standards Organization has published two new documents defining the use of a thermal imaging camera for fever screening. An essential part of the second standards paper is that only a close up image of the upper face, where a minimum of 9 pixels can be located in each corner of the eye (inner canthus), will provide a true indication of the presence or absence of fever. The widespread idea that a camera can be used to survey a group of moving passengers at a distance is entirely wrong, since it is possible to have a proven fever, yet not have a generalized increase in facial temperature, as may have been found in the SARS outbreak (Chiu et al 2005). Ring and Jung et al have measured the facial temperatures in children using the new ISO recommendations in a recent study with a hospital population. In 354 afebrile children, mean temperatures at the inner canthi of the eyes were 36.48 °C (SD of 0.49 °C) while in 52 children with clinically proven fever just prior to medication, the mean temperature was 38.9 °C (SD of 0.84 °C). These were compared with axilla temperature measured by thermometry, and forehead and tympanic membrane temperatures measured by radiometry. A good correlation was found between the eye measurements obtained from the thermogram and the clinical thermometry data, which supports the methodology described in the new standard (Ring et al at press).

However, the main concerns of fever screening with a thermal infrared camera is the uncertainty of the accuracy of some of the equipment currently used in airports, and the way in which it is employed, where the ISO recommendations are often ignored.

**Malignant diseases**

Many of the early investigations with thermal imaging some 50 years ago were entirely focused on the potential of this technique to become a useful tool in breast cancer diagnostics. For many of the reasons cited above, large expensive and unstable camera systems, before even computing and image processing was available, made this a difficult and unreliable tool. There
were undoubtedly some interesting ‘positive’ findings, but the arrival of both mammography and ultrasound effectively made thermal imaging of less interest. In addition, many proposals were made for identification of breast cancer, often based on models of heat transfer from the malignant lesion to the surface or on pattern recognition, but none of these proposals have been applied in large samples of patients or in screening programmes for breast cancer. One problem with breast imaging of surface temperature is the curved surfaces. This does mean that a single view is not sufficient and many investigators have adopted a standard series of images with full anterior, then left and right oblique positions. A single breast close up view is also used for each of these positions in order to maximize the thermal data. In some cases the patient may be imaged in the seated position with arms raised. Further anterior views with the patient lying flat on an examination couch may also be used to provide data from the inferior quadrants of the breast.

While much activity has been devoted to the complimentary role of thermography in diagnostic medicine, the monitoring of known cancerous lesions has been investigated. Monitoring chemotherapy was investigated by Keyserlingk et al (2008) in Canada (Med. Inf. Imaging Diakides 1. Ch 10 2008). They found that infrared imaging can be used to add functional information on the course of tumour development, and that these changes can precede and linger after structural tumour-induced changes have occurred. This in itself was found to be variable in a small group of patients, which might be due to the variable volume of angiogenesis, the inability of chemotherapy to affect it, or could be due to the deficiencies in scoring and grading the thermal changes. There is scope for continued research, but the authors believe that standardization of technique and better methods for quantification needs to be related to early tumour genesis, and may have a future role in studying clinical treatment regimens.

The success of locating malignant melanomas by their increased temperature on the skin surface is more interesting. This has been shown to be more easily detected in rewarming after cooling the skin by convection (Herman and Cetingul 2011) or by contact cooling (Di Carlo 1995). Melanoma identification is one of the oldest applications of infrared thermal imaging (Maillard and Hessler 1969). The value of infrared imaging for diagnosis and monitoring malignant melanomas has been a subject of contradiction in the past (Di Carlo 1995, Cristofolini et al 1981, Amalric et al 1984), but recent studies from Poland (Mikulska 2008), Argentina (Santa Cruz et al 2009) and the United States (Cetingul and Herman 2011) have shown different patterns of temperature changes in malignant and benign melanoma skin lesions. These promising results have yet to be confirmed in larger samples of patients.

Other applications

The evaluation of burns and areas of skin grafts explored initially in the 1960s in the UK has been shown to be a useful non-invasive tool of particular value where early assessment of full thickness burns improves the outcome of skin grafts.

In renal dialysis patients several papers from Austria (Maca et al 1997), UK (Allen et al 2006) and Poland (Czupryniak et al 2005) have shown that monitoring stent insertion sites and peripheral circulation with thermal imaging is an efficient means of assessing the need for revision of the arterio-venous fistula.

Thermal imaging is now increasingly used for imaging different physiological reactions induced by non-drug treatments such as massage (Bonnett et al 2006, Sefton et al 2010, Holey et al 2011, Wu et al 2009) or manual therapy (Mori et al 2004, Roy et al 2010). Temperature distribution of the skin during and after physical exercise has been reported (Zontak et al 1998, Ferreira et al 2008, Merla et al 2010). The effects of thermotherapy were recorded with
means of thermal imaging (Ammer 2004) and water filtered infrared irradiation monitored by thermography (Mercer et al 2008, Notter et al 2011). Various modalities for cryotherapy have been evaluated with thermal imaging (Selfe et al 2009, Schnell and Zaspel 2008). Recent studies have also used thermography as an outcome measure in trials investigating low level laser treatment for myofascial pain (Hakgüler et al 2003) or knee osteoarthritis (Puzder et al 2010).

Conclusion

Thermal imaging has developed considerably since it first became available for non-military applications in 1958. The technology, largely spurred on by multiple industrial applications, has become financially more viable, technically more reliable and considerably more portable. As in many other areas of imaging, computerization has had a dramatic effect on both ease and reliability of use. Finally, as recent studies have shown, standardization protocols are essential for this technique, and this must also be applied to the image processing and the selection of repeatable regions of interest.

References

Alderson J K A and Ring E F J 1995 ‘Sprite’ high resolution thermal imaging system Thermology 1 110–4
Ammer K 1991a Thermographie nach gipsfixierter Radiusfraktur Thermol. Österr. 1 4–8
Ammer K 1991b Thermographische Therapieüberwachung bei M. Sudeck ThermoMed. 7 112–5
Ammer K 1995a Low muscular activity of the lower leg in patients with a painful ankle Thermol. Österr. 5 103–7
Ammer K 2004 Temperature effects of thermotherapy determined by infrared measurement Phys. Med. (Suppl. 1) 20 75–7
Ammer K 2008a The Glamorgan Protocol for recording and evaluation of thermal images of the human body Thermol. Int. 18 125–44
Ammer K 2008b The sensitivity of infrared imaging for diagnosing Raynaud’s phenomenon and for Thoracic Outlet Syndrome is dependent on the method of temperature extraction from thermal images Thermol. Int. 18 81–8
Ammer K 2009 Cold challenge to provoke a vasospastic reaction in fingers determined by temperature measurements: a systematic review Thermol. Int. 19 109–18
Ammer K, Engelbert B and Kern E 2002 The determination of normal temperature values of finger joints Thermol. Int. 12 23–33
Anbar M 1990 Recent technological developments in thermology and their impact on clinical applications Biomed. Thermol. 10 270–6


Kanie R 1995 Thermographic evaluation of osteoarthritides of the hip Biomed. Thermol. 15 72


Mailard G F and Hessler C 1969 La thermographie des melanomes malins cutanes Dermatologica 139 353–8


Mayr H 1997 Thermografische Befunde bei Schmerzen am Ellbogen Thermol. Österr. 5 7–10


Mikulski D 2008 Dermatocopy and thermal imaging: a comparative investigation of melanocytic nevi of the skin Thermol. Int. 18 101–6


Norter M, Germond J-F, Wolf E, Berz R and Berz J P 2011 Thermography guided irradiation using water-filtered infrared-A (wIRA) and radiotherapy on recurrent breast cancer—first experiences and temperature analysis Thermol. Int. 21 47–53

Plassmann P, Ring E F J and Jones C D 2006 Quality assurance of thermal imaging systems in medicine Thermol. Int. 16 10–5


Ring E F J and Dicks I M 1999 Spatial resolution of new thermal imaging systems Thermol. Int. 9 7–14


Rogalski A 2011 Recent progress in infrared detector technologies Infrared Phys. Technol. 54 136–54

Romano C L, Romano D, Dell’Oro F, Loguluso N and Drago L 2011 Healing of surgical site after total hip and knee replacements show similar thermographic patterns J. Orthop. Traumatol. 12 81–6


Schnell H M and Zaspel J G 2008 Cooling extensive burns: sprayed coolants can improve initial cooling management. A thermography-based study Burns 34 505–8
Sefton J M, Yarar C, Berry J W and Pascoe D D 2010 Therapeutic massage of the neck and shoulders produces changes in peripheral blood flow when assessed with dynamic infrared thermography J. Altern. Complement. Med. 16 723–32
Selje J, Whitaker J and Hardaker N 2008 A narrative literature review identifying the minimum clinically important difference for skin temperature asymmetry at the knee Thermol. Int. 18 41–4
Simpson R C et al 2008 In-field-of-view thermal image calibration system for medical thermography applications Int. J. Thermophys. 29 1123–30
Smith B L, Bandler M K and Goodman P H 1986 Dominant forearm hyperthermia, a study of fifteen athletes Thermology 2 25–8
Tauchmannova H, Gabriel J and Cibak M 1993 Thermographic findings in different sports, their value in the prevention of soft tissue injuries Thermol. Osterr. 3 91–5
Thomas D and Savage J P 1989 Persistent tennis elbow: evaluation by infrared thermography and nuclear medicine isotope scanning Thermology 3 132–6
Wu C L, Yu K L, Chuang H Y, Huang M H, Chen T W and Chen C H 2009 The application of infrared thermography in the assessment of patients with coccygodynia before and after manual therapy combined with diathermy J. Manipulative Physiol. Ther. 32 287–93