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SUMMARY

Liquid crystals, encapsulated in a plastic sheet, have a clear potential for use in the medical field. However, the development and use of the technique of thermography in the U.S.A. has not been accepted in Britain. This is a result of doubts concerning the technical details of the material and its use. This study was initiated to investigate thermography to detect injuries of the foot related to sportsmen and women.

The experimental section was divided into 5 separate sections - the establishment of the photographic technique, the care of liquid crystals, the stabilization of patients' skin, the effect of pressure, spread and fade on the thermal image and the effect of skin condition on the thermogram.

The photographic technique was established first as it was to be used throughout the study and discrepancies would have led to problems in interpretation because of colour and lighting differences. Comparison of used (and incorrectly stored) film and new film showed that correct storage preserved the characteristics and therefore accuracy of the film. Monitoring of patients' skin temperature during stabilization resulted in the establishment of a 10 minute stabilization time before thermographic screening. At this point starting temperature of the foot was not significant and a definition of stability (Time range = 0-3 minutes, temperature range = + or - 0.5°C) was reached for all subjects tested.

Pressure/weight was shown not to affect the thermal image. If the effect had been positive the reliability of the whole study would have been questioned. Spread of the image was shown not to occur except at the borders of old incorrectly stored film. Fade, and therefore degree of photographic delay after patient contact with the liquid crystals, was of a linear pattern but photographs were taken immediately to avoid
potential problems of the disappearance of the image of cool areas and subsequent difficulties in interpretation. The skin condition of the subject (wet or dry) was found not to affect the thermal image and therefore made techniques to dry the skin unnecessary. These techniques of drying could seriously affect thermographic results and reliability.

Pilot studies of subjects with various foot conditions were carried out and are illustrated in Appendix I. Thermal images of subjects were taken in conditions representing the average consulting room, after the established stabilization time and after a period of 10 minutes jogging (depending on type of injury or condition). In some cases an abnormal thermogram was evident after only the stabilization period but some feet required the further stress of exercise before problem areas became apparent. Suggestions for further research and application are discussed.
Introduction

The main aim of this study is to determine the viability of liquid crystals as a thermographic screening technique. Established methodologies used mainly in the United States have caused questions concerning reliability due to variations in technique and interpretation. These variations can be attributed to a lack of objective research into the properties and characteristics of liquid crystals. This is illustrated by the limited information on methodology obtained from the literature review.

Therefore a need was identified to investigate the function of liquid crystals and their application in the medical field. The methodology established in this study was used to screen the foot as it provides a good contact area when applied to the liquid crystals. The foot is also a source of many conditions and injuries that it may be possible to identify using thermography. The application of liquid crystals forms only a small part of this study but areas of possible further research and clinical trials are discussed in detail.

The overall aim of this study is therefore to test the hypothesis that liquid crystal thermography (L.C.T.) is of value as a screening/diagnostic tool in clinical work.
1. THERMOGRAPHY AND THE DEVELOPMENT OF LIQUID CRYSTALS

1.1 History of Thermography

Early attempts at thermal testing techniques were rather crude 'frost type' tests used in the engineering industry to show unbonded areas in components. These tests were later superseded by the use of phosphors and temperature sensitive paints. In the last decade, infra-red techniques were developed primarily for the aerospace industry. Infra-red techniques subsequently found a much wider use in commercial applications, for example, in medical diagnosis (Davis, 1967). However, early thermographic equipment proved ineffective in medical use for one important reason. Essentially the equipment only displayed body temperature variations in shades of black and white, thus making it difficult to discern which temperatures the different shades indicated. Because of this, the resulting misinterpretation of results largely discredited early attempts at thermography.

In time however, more sophisticated infra-red electronic systems were developed to measure skin temperature, utilising a multiple colour scale and thus provided a major breakthrough in thermography. With this technique the temperature of the skin could be graphically represented, and its colour scale enabled greater accuracy in interpretation (Hobbins, 1982).

Infra-red thermography provides a means of remote temperature sensing. In a cool environment (20°C) the infra-red energy emitted from the skin is associated with localised changes in its temperature, which result from a disease state or stress reaction. The infra-red camera presents a video image of the temperature distribution over
the surface of the skin. This image enables temperature differences to be immediately observed, thus providing clear evidence of any abnormality. The images can, via a computer, be converted into colour coded thermograms which can be stored for later reference. Hence the equipment functions like a television system (Camera - monitor - storage - replay). Each temperature area has a known value and colour in sequence (HOT - red, orange, yellow, green, light blue, dark blue, black - COLD). The computer can give a temperature value for any selected area (Ponsonby & Ring, 1980).

However, electronic thermography has faced a very clear problem, namely its cost. When the equipment was first available in America its cost was between $30,000 and $50,000 and as such, was considered uneconomic. In addition this type of equipment, because of its size and complexity of operation, was not easily moved from one position to another (Hobbins, 1983).

1.2 Liquid crystals

A new thermographic technique was then developed using cholesteric liquid crystals. The first description of the nature of liquid crystals was given by Reinitzer in 1888, the term cholesteric arising from its original association with cholesterol derivatives. However, despite this early discovery, most of the work on cholesteric liquid crystals was not carried out until after 1969 (Saeva, 1979).

The liquid crystals provide inexpensive, reproducible thermographic images. Initially the crystals were available in paint form in which the liquid was brushed on to the surface being tested. This method required several bottles of liquid crystal paint as each different paint covered only a small temperature range (approximately 2°C) and therefore required mixing to extend the range of temperature measurement needed
for screening of the skin.

A major disadvantage of this technique however, was its method of application, e.g. when measuring skin temperature. The skin was degreased with petrol, a black base lacquer was applied using a soft brush and the liquid crystal paint was brushed on top of this base layer (Lelik, 1979). In addition to the time and difficulty in application it can be surmised that such a procedure would lower skin temperature due to evaporation of the petrol in the early phases whilst raising the skin temperature in the later phases due to the prolonged occlusion of the skin under the layers of base lacquer and liquid crystal paint. The accuracy of the data produced would therefore need to be questioned.

Liquid crystal development has progressed and now the crystals are available in encapsulated sheets. The liquid crystals are finely dispersed within a polymer matrix and are backed with Mylar (a trade name for black polyethylene glycol terephthalate sheetsing). The crystals are protected and are therefore not subject to contamination by dust and smudging, which would cause the unprotected crystals to lose their characteristic properties within days. Provided that handling precautions are observed, the crystal films will retain their colour characteristics for a minimum of 1 year (Edmund Scientific, 1980).

The sheets can either be used on their own or can be incorporated into a lightweight frame. The liquid crystals display colour in the opposite way to the electronic equipment, the lowest temperature being displayed as dark brown. This changes with progressive temperature elevation from tan to red/brown, yellow, green, light blue and dark blue (Pochaczevsky, 1982).
2. **Physical Properties of Liquid crystals**

Liquid crystals are organic substances that, when passing from the liquid to the solid phase, assume an intermediate phase (Mesomorphic state). The molecules of liquid crystals are arranged according to three molecular patterns as illustrated in Figure 1. These are smectic (A), nematic (B) and cholesteric (C) each having different physical characteristics.

Only liquid crystals in the cholesteric phase are suitable for application to this study due to their particular optical properties. They are named cholesteric because this type of crystal contains mainly compounds of cholesterol.

e.g. Cholesteryl Oleyl Carbonate

\[ \text{CH}_3(\text{CH}_2)_n\text{CH}:\text{CH}(\text{CH}_2)_m\text{OCOOC}_{27}\text{H}_{45} \]

Due to the structure of cholesteric crystals they display optical properties. The optic properties are a result of long rigid lathe-like molecules which have the ability to change structure (pitch) in response to temperature change.

The crystals flow like a liquid and simultaneously exhibit the optical properties by selectively scattering light. When white light shines on cholesteric liquid crystals they reflect coloured light. They selectively reflect only one wavelength at each angle (pitch) and when light comes from several directions at once the resulting mix of colours is seen as iridescence. A change in temperature causes a shift in molecular structure, thus altering pitch, and therefore a different colour is observed. The layers of crystal, placed one upon the other, trace out a helical path where the pitch is influenced by temperature change. As temperature increases, the pitch decreases, and the molecular layers move
Fig 1. Structure of liquid crystals

Fig 2. The Effect of Temperature on Pitch of liquid crystals
from Tonegutti et al (1980)
closer together; as temperature decreases, pitch increases, so the molecular layers move further apart, as shown in figure 2.

As the wavelength of the coloured light reflected by the crystals is directly linked to the pitch value, the temperature influencing the pitch will thus determine the colour of the reflected light. In general the spectrum of wavelength of each value of pitch is very narrow, which means that a relatively small fluctuation of temperature (and therefore pitch) is sufficient to change the colour of reflected light. See figure 3.

The viewing angle must be kept constant because the wavelength of maximum scattering is a function not only of the angle of incidence but also of the viewing angle of the scattered light.

A low temperature with a corresponding high pitch value produces chromatic tones, which appear on the surface of the crystals corresponding to the longest wavelengths of the visible spectrum (red and its nuances). Following chromatic variations the colours change through the following sequence: yellow, green to blue/violet; which is the shortest wavelength of the visible spectrum (i.e. low pitch values). This is illustrated in figure 4, with 20°C– 25°C and 25°C– 30°C range films.

The crystals are sensitive to a very wide range of temperatures (from -20°C– 200°C) and can detect temperature changes as small as 0.1°C. By means of a special process of mixing, compositions are manufactured which respond to the thermal range required. The crystals also have the property of a quick response to temperature change. Surface colour change can be seen in approximately 0.2 seconds.
Optical Characteristics of liquid crystals in thermography
Fig 4 Effect of temperature on Wavelength of Colour produced

from Edmund Scientific (1980)
3. LIQUID CRYSTALS - SYSTEM DEVELOPMENT IN THE MEDICAL FIELD

3.1 Liquid Crystal Paint

This was the first use of liquid crystals in which the crystals were applied to the skin in paint form on top of a black base layer allowing the light to reflect from the crystals and to produce a visible thermal pattern. Lelik (1979) used this method to diagnose which ligaments were involved in ankle sprain injuries and to show when recovery was complete, i.e. when areas of local inflammation, as shown by temperature elevation, had disappeared in relation to the normal ankle. Although this method was time consuming and the liquid crystal paints needed mixing to obtain the correct temperature range, the thermal pattern could be observed for an extended period of time, i.e. up to 20 minutes after application.

3.2 Rigid Films

Liquid crystals are now available in encapsulated sheets which can be applied directly to the skin and then, when the thermal pattern has been photographed, can be removed and re-used. Tonegutti et al. (1980) describe equipment designed by Bayer, used extensively in the diagnosis of breast cancer. A moveable support incorporates a metallic frame which connects a liquid crystal plate with a photographic recording system. (Four different plates cover a temperature range of 31°C-34°C). The photographs of the breast area are taken when the crystal sheet is still in contact with the skin, using a Polaroid camera (Figure 5). The photograph produced is viewed in a specially designed enlarger.

Ponsonby & Ring (1980) used rigid films mounted on a platform on which the patient stood (Figure 6). The subject's feet were placed on the film and the observer viewed the
Fig 6 Platform mounted rigid film from Ponsonby & Ring (1980)

Subject stands on film plate

Liquid crystal plate

Reflected Thermogram

Mirror system

from Tonegutti et al (1980)
thermogram reflected in a mirror situated within the platform. The image was then photographed to provide a permanent record.

The rigid type film is also used in the manufacture of forehead thermometers (See Section 4.5).

3.3 Flexible Liquid Crystal Films

During the course of this study there has been extensive development and use of flexible liquid crystal film in many medical areas. Pochaczevsky (1983) reports on the Flexitherm System - the most widely used equipment. The sheaths of liquid crystal film are mounted on sealed boxes that can then be inflated to provide an 'air pillow' which can be contoured to the body area under examination (Figure 7). The boxes range from 26°C-35°C and are slotted into a framework which incorporates a fixed camera and flash unit to provide permanent records of thermographic patterns. The film is lifted slightly away from the skin surface before photography to eliminate distortion and glare.
Fig 7  Inflatable liquid crystal film system from Pochaczevsky (1983)

- **Clear plastic sleeve** pressed against patient
- **Clear plastic frame**
- **Inflated liquid crystal material**
- **Air pump**
4. CURRENT USES OF LIQUID CRYSTALS

4.1 Breast Cancer Detection

The use of liquid crystal technology in the screening for breast cancer is perhaps its most widespread application. It gained acceptance as the need for further preventative screening became apparent, due to the rising number of cancer cases. It has been shown that in mass asymptomatic screening, 10% of those tested present significantly abnormal thermograms. In 68% of this abnormal group carcinoma was subsequently positively identified (Hobbins, 1983). Breast cancer is the leading cause of death in women aged 35-54 years old. Most patients have well established metastasis by the time of diagnosis, but only 30% of breast cancer cases are diagnosed before the age of 50 (Oswald et al., 1982).

Strax (1982) argues that breast cancer can be cured if detected at the right time. However this can be at a stage when the patient has no physical signs and minimal symptoms of the disease. The need for early detection and treatment is emphasised by Gautherie & Gros (1980) when discussing the growth rate of cancer lesions. Since the doubling time of mammary carcinomas ranges from 50-700 days, early effective treatment may be particularly important for the more rapidly progressing lesions.

These findings illustrate the need for regular screening of asymptomatic women to detect changes that may be taking place. Thermography by liquid crystal technology represents a useful alternative to current investigations. Mammography is the main current test conducted, but it involves radiation exposure to produce X-ray representations of the breast structure. Thermography using liquid crystals, is non-invasive, has a low cost and the ability to point to malignant diseases at an early stage. In addition it can
provide information related to metabolic, vascular and hormonal phenomena (Gautherie et al., 1982).

A review of the literature on clinical thermography suggests that the technique is a harmless, non-specific method, useful in the detection of breast cancer and in the evaluation of benign diseases (Nyirjesy et al., 1977). Thermography uses flexible plates of encapsulated liquid crystals which are held in contact with the breast. The resulting thermal pattern is recorded by photography for future diagnosis (Gautherie et al., 1982).

The liquid crystal thermogram shows a combination of metabolic and vascular changes that are reflected by changes in temperature and in the vascular pattern (Anon. 1981). These factors are equally important in determining abnormality, and these findings show the ability of thermography to depict cancer when the patient is still asymptomatic. The importance of the detection of heat production is shown by the unequivocal relationship between growth rate and metabolic heat production. Gautherie & Gros (1980) state that the more rapidly growing lesions, with shorter doubling times (45-50 days), show progressive thermographic abnormalities consistent with the increased metabolic heat production associated with these cancers.

Kelker & Katz (1980) quantify this further by noting an increase of 0.9°C-3.3°C in skin temperature, over a rapidly growing breast carcinoma, in relation to surrounding healthy tissue, and Nyirjesy et al., (1977) note from a review of data that breast cancer causes heat emission in the majority of patients, although no indication of the exact percentage is given.

The technique of liquid crystal thermography can therefore detect the vital temperature changes in the breast, but in no
case is the diagnosis of cancer made on the basis of thermography alone. This is due, in part, to false positive and negative results having occurred with this technique. The extent to which this is a function of variations in methodology is unknown and as such requires further investigation (Oswald et al., 1982). Nyirjesy et al., (1977) note that the false negative findings vary from 3%-29% and that these fluctuations occur according to the equipment and method of interpretation of the thermograms. In their study Kelker and Katz (1980) observed 5 false negatives (8%) within a total of 64 patients. False positives were also observed and produced a similar percentage (10%). These results, they suggest, appear dependent on the technique used and the classification of results.

There is a clear need to examine the methods involved in this technique in order to improve its effectiveness in the detection of cancer. Thermography does, however, have an important role in drawing attention to the possibility of cancer at an early stage (Gautherie & Gros, 1980).

Liquid crystal thermography can also be applied to other areas of breast care. It can be used as a highly successful indicator in the following areas:

1. Quantification of hormone influence on the breast and to monitor therapy programs in the different mastopathies.

2. Establishment of a thermal prognosis in patients with demonstrated breast cancer.

3. Follow-up of the breast in patients with previous breast cancer.

4. Observation of the breast circulation in response to diet (Vitamin B6, Vitamin E) and drugs (hormones,
Liquid crystal thermography techniques have been shown to be of vital importance as an early warning system that can be used in conjunction with other tests to determine the possible existence of cancer and as a method for the follow up of patients. Thermography should be used extensively by the primary care physician and the gynaecologist in combination with physical examination and other methods (Gautherie et al., 1982).
4.2 Back Pain and Associated Conditions

Rubal et al. (1982) estimate that 80% of the American population will seek aid for back pain during adult life and further, that for some, back pain is transient, but for others such pain entails a loss of income, prolonged hospitalisation or permanent disability. Pain is a subjective experience difficult to describe and measure objectively, but advances in medical thermography offer a method of verifying the existence of back pain symptoms and a means of isolating areas of pain, thereby aiding the diagnosis and making specific management possible (Wexler, 1981).

Pochaczevsky & Feldman (1982) report that liquid crystal thermography of the spine and extremities is useful in assessing numerous conditions, and they state that clinical experience shows that contact thermography can objectively document the subjective complaint of pain. They believe thermography can show demonstrable alterations in skin surface temperature corresponding to the distribution of pain, and that an abnormality can exist despite other normal examinations which include myelography (X-ray of the spinal cord after injection of a contrast medium). Rubal et al. (1982) also remark on surface temperature when they suggest that with structural injury, the abnormality is reflected on the surface of the body as a temperature elevation resulting from inflammatory and metabolic changes. Wexler (1981) states that a temperature increase of 1°C, when compared with the opposite side, can be considered abnormal and may indicate physical damage.

The following conditions, according to Pochaczevsky (1983), can be detected by liquid crystal thermography:

1. Confirmation of suspected spinal root compression syndromes, as seen in association with herniated discs and osteophyte formation.
2. Spinal canal stenosis (narrowing of canal).

3. Subluxation and hypertrophy of superior vertebral facets.

4. Documentation of pain in spinal musculoligamentous injuries.

5. Inflammatory, infectious, traumatic and neoplastic diseases of the spine.

Carpenter (1982) also notes some of the above conditions when she refers to liquid crystal thermography being used to detect pain from such sources as sensory nerve irritation, muscle spasm, a bulging disc, infection, or bone tumour. She also points out that malingerers can be identified.

Thermography has been most widely used in root compression syndromes and Wexler (1981) describes the technique as a diagnostic tool that may well represent a significant step in the evaluation of acute nerve root syndromes, where findings are usually manifested by a relatively cold area along the course of the dermatomes that are affected. He explains that as a nerve root is irritated, it sends an excess of impulses along the course of the nerve, producing sympathetic hyperactivity. This hyperactivity causes vasoconstriction in the blood vessels surrounding the nerve. With a thermogram the vasoconstriction can be seen as a relatively cold area because of a reduction of blood supply in these areas.

Pochaczevsky (1983) reports that liquid crystal thermography has demonstrated a high degree of accuracy and correlates well with clinical and surgical findings. In a study of 48 patients who underwent surgery, he found that thermography had been accurate in 92% of cases and myelography in 85% of cases. Wexler (1979) also considered the value of thermography in a study of 86 patients. In 92% of cases,
thermography correlated well with subsequent surgical findings as opposed to myelography where the comparable figure was 83%. However, the significance of the differences between thermography, myelography and surgical findings was not documented in either study.

The liquid crystals accentuate thermal and vascular pathology with a high contrast thermographically calibrated colour display. In cases of undetermined back pain Wexler (1981) suggests that thermography should be the first screening procedure since it is a low cost, non-invasive technique which can be carried out before the need for further tests is evident.
4.3 Sports Injuries

The use of liquid crystal thermography in sports medicine has not been widespread, but there is potential for its development in the diagnosis and monitoring of recovery, in both acute and chronic injuries.

The heat increase involved in tissue damage (see 6 - Physiology), whether immediate or of gradual onset, can be detected by liquid crystals. In acute cases Henahan (1982) studied the amount of temperature increase at the site of injury in order to determine length of recovery. He found that an increase of 1.5°C-2.0°C, associated with lacerations or haematomas, indicated that athletes could return to sport within 3-4 weeks, but that higher temperatures (4-5°C) necessitated a much longer recovery. He also suggested that thermography could be used to evaluate old and neglected recurring injuries and to determine their response to surgery.

The most common injury that has promoted the use of thermography is that of tennis elbow. Binder (1982) observed "hot spots" of between 1° and 3°C in the lateral epicondylial region of the humerus in 48 out of 50 patients with clinically diagnosed tennis elbow. The warmer the "hot spots", the more severe were the clinical symptoms such as pain and tenderness. He noted that as the patient responded to treatment with hydrocortisone or ultrasound therapy, the abnormal thermographic patterns were reduced and eventually ceased.

F. Lelik* (1979) used liquid crystals to study ankle sprains and states that clinical examination and thermography enable the orthopaedic surgeon to form an objective diagnosis. He suggested that if results of thermography are positive both above the fibula malleolus, and in the area of ligamentous damage, it can also be stated, before X-ray, that the ligament tear is complicated by bone fracture. In contrast however, if
positive results are observed only above the fibula malleolus, then there is an isolated fracture without ligamentous damage. He also states that thermography can show that the healing process in ligament tears is often not complete even after the disappearance of clinical symptoms such as swelling. This, he concludes, may help to prevent further damage and other complications during rehabilitation of this type of injury.

In overuse conditions, especially of the foot, thermography can be used to detect heat build-up before appreciable tissue damage occurs. Any pinching, abrasion, cramping or bruising at the foot-shoe interface will produce a rise in temperature, and pressure from football studs on the metatarsal heads may produce an increase in temperature of up to 5°C (Ponsonby & Ring, 1980). The detection of this heat increase before its return to normal (about 1 hour) can prevent the development of inflamed bunions, blisters and widespread bruising which can be a particular problem to sportsmen and women.
4.4 Deep Vein Thrombosis

Deep vein thrombosis (D.V.T.) describes the condition usually affecting the lower limbs, of an aggregation of blood factors which frequently cause vascular obstruction at the point of their formation (Dorland, 1981). D.V.T. of the lower extremities is a potentially serious condition since one of its consequences - pulmonary embolism - is a common cause of morbidity and mortality, particularly in the post-operative period (Richie et al., 1979).

To detect D.V.T., the normal range of leg temperature must be known. The thighs are normally 4°C warmer than the feet. Therefore, temperature should show a progressive gradient in this direction. However, relatively cooler pre-patellar and pre-tibial areas should be present in normal leg temperature. Extremity temperature should be equal in the two lower limbs at any level (Richie et al., 1979). Unilateral loss of normal pre-patellar or pre-tibial coolness indicates D.V.T. In addition, Aronen et al. (1981) noted the difference in temperature of the diseased and the contralateral side to be between 1°C and 4°C. Furthermore, if D.V.T. is confined to soleal or posterior tibial veins, the areas of increased temperature may be localised to the lower calf, and their delayed response to cooling would indicate D.V.T. (Cooke & Pilcher, 1973).

Temperature change is the main factor involved, and liquid crystals have therefore been widely used in the primary diagnosis of this condition. Liquid crystal thermography is a new, improved technique developed for the diagnosing of D.V.T. and has produced a percentage agreement of between 62% (Aronen et al., 1981) and 90% (Pochaczevsky et al., 1982) with ascending phlebography (the detection of vascular obstruction using dye injected into the leg which is then X-rayed). The thermograms are produced by placing liquid crystal sheets on the patients'
calves and thighs while they are in a prone position. The resulting image is photographed and diagnosis can then be made (Jensen et al., 1983).

However, false positive and negative results do occur, and in a study of 141 patients with suspected D.V.T. Aronen et al., (1981) found 19 false positive and 3 false negative results. (The number of false positive results was also relatively high). In a study conducted by Jensen et al., (1983), they obtained 16 false positive results from a patient total of 69. However, Lockner et al., (1980) noted that the frequency of such false positives may be minimised by performing thermography after exercise, since a normal heat pattern is accentuated in an unaffected leg after 3 minutes walking on the spot. In contrast, after similar exercise, the affected leg shows an abnormal network of linear hot spots crossing the anterior tibia.

A percentage of false positive results may be attributed to a patient's history of leg disease. Such diseases include post-thrombotic changes and deep venous insufficiency. In these cases phlebography or other methods of screening are required to confirm D.V.T. due to the non-specific result of a positive thermogram (Aronen, 1981).

Liquid crystal thermography is an important preliminary screening method for use in patients with suspected acute D.V.T., because it is sensitive, economical and is non-invasive. If the finding is negative, the presence of thrombosis is highly unlikely. However, if the finding is positive the order of investigation, with thermography as a primary indicator, reduces both the cost and hazards of other screening methods.
4.5 Plastic Strip Thermometers

Plastic strip thermometers are small, flexible, plastic strips which register a body temperature reading after being pressed to the forehead for one minute. The thermometer is divided into 5 sections, each containing cholesteric liquid crystals, as shown in figure 8. These crystals change colour in response to heat; from black (when no heat is registered) to tan, to green, to blue and in reverse order when cooling. The different colours correspond to the lower, middle and highest temperature in the specified range for a given section. A reading of body temperature to the nearest degree Centigrade/Fahrenheit is obtained by observing the colour change in the highest numbered section that registers (Lewit et al. 1982).

Plastic strip thermometers have been widely sold and used but have received mixed reviews. Hall and Oliver (1971) recommended the use of liquid crystal monitor tapes attached to the abdominal skin of newborn babies as a quick and accurate means of measuring body temperature. Burgess et al. (1978) suggested that liquid crystal strips may be used as a convenient method for the routine monitoring of temperature trends during general anaesthesia, in cases where it is not necessary to measure core temperature precisely.

The strip thermometer is criticized by Reisinger et al. (1979) in a report that compared the temperature taken with an electronic thermometer to those taken with three plastic strip thermometers. In their study of 152 febrile or afebrile children, they found that the plastic strip thermometers detected only 23 of the 30 children who were classified febrile according to the electronic thermometer. They concluded that there appeared to be an appreciable risk that reliance on the strip thermometer might delay recognition of a serious illness. Lewit et al. (1982) confirmed these misgivings by suggesting
Sections of Encapsulated Liquid Crystals

Instruction Leaflet Feverscan™ U.S.A. (Trade Name)
that there appeared to be an insufficiently high degree of accuracy to warrant the use of strip thermometers, even as gross screening devices. In observations of 351 patients, they found that the plastic strip thermometer readings were lower than mercury thermometer readings in 76% of the cases studied. They drew attention to factors which might contribute to its inaccuracy. These included the condition of the skin on the forehead, the age of the patient and variations in the actual method of taking the temperature.

In conclusion they advocated that further investigation of the plastic strip thermometer be undertaken, and observed that such tests should have predated marketing.
4.6 Insurance Claims

A relatively new application of liquid crystal thermography is within the legal profession where its use has been demonstrated in a number of cases. Californian courts, for example, now routinely accept thermographic evidence in order to settle insurance claims where medical testimonies from physicians are conflicting, (Hobbins, 1983). Wexler (1979) notes that thermograms have a very practical use for insurance claimants. If a thermogram is positive an injury exists even though the injury may not be recent. However, once the existence of an injury has been established further examinations can be made to determine details of that injury. In contrast, a negative thermogram may result in the withdrawal of a compensation claim.

Meyers & Meyers (1980) suggest that the thermograms taken serially provide a temporal perspective in relation to pain and injury. Such a diagnostic tool, they report, can either enable a claimant to confirm his continuing subjective disability or can support a "Fit to return to work" recommendation.

Wexler (1979) predicts that the use of thermography in legal cases will continue to develop because of the objectivity of the technique, providing however, that there is uniformity in the method of application and in the diagnosis of results. Nevertheless, the technique of thermographic screening in insurance claims has its critics, and other areas of the U.S.A. (with the exception of California) are concerned about discrepancies in methodology and question the potential abuse of the procedure in order to win a case (Norris, 1981). Nyirjesy et al., (1977) question the effectiveness of liquid crystal thermography in isolation and warn that thermography should only be used as an adjunctive procedure in medicine and that it should not be used alone for any purpose.
Opinion is therefore conflicting concerning the use of thermograms in a legal context, but Meyer & Meyer (1980) suggest that the procedure will become more acceptable to lawyers and insurance companies as research continues to improve methods and the resulting diagnosis. The technique will then be a significant aid in either the prosecution or defence of personal injury litigation cases.
4.7 Additional Medical Applications

1. Dermatology

Liquid crystal thermography (L.C.T.) can be used in dermatology to evaluate the extent of burns and the viability of skin grafts (Sowa, 1979). Raskin & Viamonte (1977) suggest that L.C.T. can also be used to detect positive patch test results only 6 hours after the application of an allergic substance to the skin, and to monitor the cause of allergic reactions. Furthermore, Meier et al. (1975) have used L.C.T. to identify thermal instability prior to the onset of pressure sores and to detect necrotic tissue.

2. Haematology

L.C.T. can identify bleeding into the joints of haemophiliacs and can assess the effects of physiotherapy on these cases (Hobbins, 1983). It can also monitor the effects of therapy on patients receiving vasodilators and thrombolytic agents (Holm et al., 1974).

3. Obstetrics

When complications in the later stages of pregnancy necessitates an operation, the position of the placenta must be accurately determined before surgery. L.C.T. can be used in this instance because of a 2°C higher temperature in the skin region above the placenta (Meier et al., 1975).

4. Orthopaedics

The identification of stress fractures, the monitoring of the progress of fracture healing and the diagnosis of Paget's Disease (a bone disease resulting in weakened, deformed bones of increased mass) can, suggests Hobbins (1983), be determined...
by L.C.T. He also states that L.C.T. can be used in the operating theatre and on comatose patients to check possible circulatory restrictions after plaster casts have been applied.

Fisher (1981) notes that L.C.T. can be used as an indicator for the selection of the site of amputation which will ensure future limb viability, and as a monitoring device for infected or sensitive stumps. He also suggest that L.C.T. can assess the skin condition of the feet of neuropathic patients and cases where prostheses have been fitted.

5. Pharmacology

The reaction rates of chemical substances introduced into the blood stream which produce allergic skin reactions can be tested by L.C.T. The reaction is due to the release of histamine and resultant heat production is what causes skin redness. (see Section 6) The effect of medication to combat allergic reactions can also be monitored using L.C.T. (Meier et al, 1975).

6. Psychiatry

Hall (1978) suggests that after L.C.T. application many cases of psychogenic pain are shown to be partly physical. He states that 43% of patients with the diagnosis of 'psychogenic pain' have one or more undiagnosed medical problems. However, Lerman (1984) notes that a normal thermogram of a patient with extreme pain may indicate a psychogenic origin.

7. Rehabilitation

Rehabilitation specialists and physiotherapists can use L.C.T. to show areas of heat caused by the 'inflammatory reaction', which causes pain to the patient. The progress made in the healing of these injuries can therefore be measured.
during return to function, by observing the decrease of these heat areas (Hobbins, 1983).

8. Rheumatology

Robbins (1983) suggest that L.C.T. can objectively assess the inflammatory reaction caused by joint diseases without the patient's exposure to the invasive radiation of X-rays. Kelker and Katz (1980) also noted that L.C.T. can be used to diagnose the inflammation of joints and can, with regular thermograms, control the dosage of anti-inflammatory drugs.

9. Veterinary Medicine

As in human rehabilitation, L.C.T. can measure the healing process of animal injuries, particularly in horses, moreover it can be used to screen race horses for injuries (Hobbins 1983).
5. **ANATOMY AND FUNCTION OF THE FOOT**

5.1 **Anatomy of the Foot**

For detailed anatomy, readers should refer to standard anatomy books (Gray, 1980), (Cunningham, 1972).

5.2 **General Features**

The foot is an arched structure consisting of 26 bones, as illustrated in figure 9. The structure has two main functions - support and propulsion. It combines stability with flexibility and its propulsive action is that of a flexible lever. The foot has a longitudinal arch being divided into inner and outer sections.

The inner arch passes from the calcaneum through the talus and then distally, the outer one through the cuboid avoiding the talus. The transverse 'arch' of each foot forms only half an arch, but when the two feet are placed together make a complete dome. The arches function to distribute the weight of the body between the heel and the metatarsals (Klenerman, 1976).

5.3 **The Foot in Stance**

As body weight passes through the foot to the ground, the bones of the foot gravitate into firm apposition with a tightening of the plantar ligaments, until the arched framework becomes rigid and relatively non-yielding to further pressure. Morton (1964) described the weight distribution of the foot in stance in terms of a division of 60 lbs (27.2 Kgs) per foot, 50% at the heel and 50% at the forefoot, as shown in figure 10. This became the accepted model for weight distribution. However, Morton’s work is questioned by Kotwick (1982) when he states that Arcan and Brull (1975) found a 54% heel, 46%
Fig 9  Bones of the Right Foot
Cunningham (1972)

- Distal phalanx
- Middle phalanx
- Proximal phalanx
- Sesamoid bone
- 1st Metatarsal
- 5th Metatarsal
- Medial
- Intermediate (Cuneiforms)
- Lateral
- Navicular
- Cuboid
- Superior surface of talus
- Lateral process of talus
- Part of upper surface of calcaneus
Fig 10  Weight Distribution of the foot in stance
Morton (1964)

TOTAL
10 POUNDS
(4.5kgs)

TOTAL
20 POUNDS
(9.0kgs)

TOTAL
30 POUNDS
(13.6kgs)

- Points of bony contact

50% Heel )  60 lbs (27.1kg) per foot
50% Forefoot )
forefoot weight distribution, and Aharonson et al. (1980) found as much as a 61% heel, 39% forefoot distribution.

5.4 The Foot in Locomotion

The foot acts as a semi-rigid (dynamic) lever during landing and take-off phases. Between these phases it becomes less rigid and can therefore adapt to differences in the surface underfoot.

At heel strike, the foot is pronating and while the heel is the principal load-sustaining part of the foot, the forefoot is relatively mobile. From this point in the cycle, until after the foot leaves the ground, the foot is supinating. Thus, at a time when load is being transferred to the forefoot, supination of the foot converts it into a semi-rigid lever in preparation for the push-off phase.

The gastrocnemius and soleus muscles prevent dorsiflexion of the ankle beyond about 10° or so that as the supporting leg passes the vertical position, the heel lifts from the ground and the foot pivots about the metatarsal heads. The calf muscles exert their early propulsive thrust by contracting isometrically. When active plantarflexion occurs, there is almost simultaneous flexion at the knee so that this period of calf muscle activity serves principally to accelerate the leg forwards and upwards to begin the swing phase.

Because the line of the metatarsal heads is not transverse to the direction of walking, but inclines laterally and backwards by about 30°, as the foot tips forwards on the metatarsal heads the lateral metatarsal heads tend to leave the ground and the centre of the load moves medially. Among mechanisms that diminish this effect is external rotation of the tibia producing supination of the foot.
The dorsiflexion of the toes that occurs in the second half of the stance phase as the heel leaves the ground has the effect of increasing tension in the plantar aponeurosis. This produces a relative shortening of the base of the arch of the foot, thus the arch rises and the foot effectively increases in tension for toe-off. (Klenerman, 1976).

5.5 Disorders of the Foot

Imperfections and injury to the bones and ligaments which give the foot its structural stability and its normal distribution of weight, increases the work load of the muscles on the affected side with an associated disturbance in posture and balance, which in turn produces related symptoms (Morton, 1964).

Abnormal weight distribution and incorrect function can produce symptoms in the foot, knee, hip and back, but may initially be revealed in the foot as blisters, bunion development, skin, muscle and joint soreness and sprains. Many of these conditions may be detected by liquid crystal thermography because of the associated inflammatory reaction causing swelling, heat and pain. Thermography may therefore be able to detect these symptoms at an early stage and through corrective treatment prevent further damage.

Liquid crystal thermography, with its capacity to detect heat increase on the surface of the body, can therefore show the inflammatory response of heat in either acute or chronic overuse injuries and possibly also in small bone fractures near to the skin surface. Further it can show, over a period of time, the reduction or disappearance of heat areas which indicate the end of an inflammatory response. The degree of improvement can thereafter be ascertained (Schmitt, 1982).
6. CAUSES OF TEMPERATURE INCREASE IN INJURY AND OVERUSE CONDITIONS (PHYSIOLOGY)

The physiological reaction of the human body to localised injury is manifested by swelling, pain, loss of function, redness and heat in varying degrees of intensity. The factors important to this study are those of redness and heat production the former being, in many cases, the physical sign of the latter.

Redness and heat are due to the dilation of numerous small local blood vessels, increasing the vascularity at the site of injury. This increased blood flow to the injured area in turn increases the delivery of plasma proteins and phagocytic leukocytes which are triggered by the release of histamine, kinins and prostaglandins.

Histamine is present in many cells and is released due to mechanical disruption of injured cells. It causes vasodilatation and increased vascular permeability. The kinins are a group of polypeptides that dilate arterioles, increase vascular permeability and induce pain. Certain prostaglandins induce vasodilatation, increase vascular permeability and contribute to the pain reaction.

The release of these chemicals continues to increase the permeability of the small vessels thus allowing plasma fluid and solutes to move out of the circulatory system and into the inflamed tissues; which in turn results in oedema. Eventually the blood flow is slowed down due to the 'clumping' together of erythrocytes (red blood cells) and the resultant resistance to blood flow. As the inflammation progresses, blood flow through the small vessels in the injured area slows down and eventually stops. The injury site is then sealed off by the formation of fibrin in the tissues which limits the spread of toxic products and allows the healing process to take place.
This reaction is a protective response and can be diffuse (covering a large area) or focal (confined to a limited area). It can also be acute, which is usually of sudden onset, or chronic, which is a slower process marked chiefly by the formation of new connective tissue. A chronic condition may be the continuation of an acute episode or a prolonged response, and it usually causes permanent tissue damage. (Spence and Mason 1979).

The inflammatory reaction then, is initially a protective response and subsequently one of repair and healing. The inflammation can be either in soft tissue or bone, where a minute stress fracture, not visible on X-ray, can set up a physical inflammation in which the blood supply to the area is increased and therefore local temperature elevation occurs. Paradoxically this results in calcium absorption from the bone near the fracture (Devas, 1975). The fracture eventually becomes bigger and can finally be detected on an X-ray.
7. FACTORS THAT MAY AFFECT THERMOGRAPHIC PATTERNS

When using liquid crystal thermography to diagnose and monitor injuries and overuse conditions several factors must be considered if accurate thermographic patterns are to be obtained.

Clark (1982) suggests that further research is needed in order to determine factors that can influence a thermogram, and that recent patient history must therefore be considered.

Henahan (1982) noted that many drugs act on the hypothalmus and on other brain centres involved in controlling the body's thermoregulatory system. For example, methysergide maleate, used in the treatment of migraine, can cause a skin temperature decrease of as much as 10°C because it is an antagonist of serotonin, which regulates body heat loss. Vasodilators, particularly when used locally on injury sites, can confuse the interpretation of a thermographic reading. Henahan (1982) suggests that local "hot spots" caused by the use of vasodilators can persist for approximately 24 hours after application. Hobbins (1983) reports that the interpretation of thermograms can also be confused by drugs or ointments that cause an allergic skin reaction resulting in raised skin temperature.

Wexler (1981) studied the effect of hot and cold packs on the skin temperature and the resulting thermograms: he found on immediate removal of the packs that although initial thermograms would be inaccurate, these become normal after 40-45 minutes as the skin returned to its original temperature.

The use of local anti-inflammatory creams and hot and cold packs are common treatments in the type of condition considered in this study. Before using liquid crystal thermography then, it is essential to establish whether these treatments have been used recently and if the patient is taking drugs or using creams that may affect the accuracy of the thermograms.
8. INJURIES AND OVERUSE CONDITIONS SHOWING HEAT INCREASE IN THE SKIN OF THE FOOT

The following list of conditions which affect the foot all emit heat as part of the inflammatory process as discussed in section 6. However, this study is concerned particularly with injuries and disorders of the foot caused by incorrect function and abnormal weight distribution (see Section 5). Therefore, some of these conditions, whilst listed, will not be considered in this study.

Liquid crystal thermography is a non-specific indicator of raised skin temperature, and consequently difficulties arise distinguishing specific abnormalities. Nevertheless, the fact that these conditions all emit heat may be useful, in conjunction with physical examination, for diagnosis and perhaps, more significantly for showing the progress of recovery or deterioration.

1. Blisters

An elevation of the epidermis containing serous liquid. May be superficial or deep.

2. Bruised Heel

Repeated heavy landings on the heel cause rupture of the fibrous septa between and under the surface of the calcaneum and the skin, resulting in the crushing of the skin by bone (Williams & Sperryn 1976).

3. Callosities

Localised hyperplasia of the horny layer of the epidermis, due to pressure or friction.
4. **Corns**

Horny induration and thickening of the stratum corneum of the skin, causing inflammation.

5. **Hallux Rigidus**

Osteoarthritis of the metatarso-phalangeal joint of the great toe causing limited flexion and extension. Force dorsiflexion of the painful joint on walking is the main source of disability (Adams, 1981).

6. **Hallux Valgus**

Lateral deviation of the great toe at the metatarso-phalangeal joint. Secondary changes are initially the formation of a bursa (bunion) over the medial prominence of the metatarsal head, followed by osteoarthritis of the metatarso-phalangeal joint (Adams, 1981).

7. **March Fracture**

Stress fracture of the metatarsal bone. The most common fractures are those that occur in the second or third metatarsal shafts. Stress fractures are caused by repeated muscle contracture that resists the weight of the body passing through the bones of the leg to the ball of the foot. This occurs in excessive or unaccustomed exercise, e.g. army marching (Devas, 1975).

8. **Morton's Metatarsalgia (Interdigital Neuroma)**

Irritation causing fibrous thickening of the digital nerve of the 3-4 cleft proximal to its point of division into terminal branches. Occasionally the nerve to the 2-3 cleft is the one affected. Causes pain in the metatarsal region,
radiating to the toes along the affected nerve branch (Morton, 1964).

9. **Plantar fasciitis**

Lesion affecting the soft tissues at the site of the attachment of the plantar aponeurosis to the inferior aspect of the tuberosity of the calcaneus. The condition is believed to be inflammatory (Adams, 1981).

10. **Postural Strains**

General ache in the front of the foot, often under the second and third metatarsal heads. Usually caused by a postural defect, i.e. mild pes planus (Williams & Sperryn, 1976).

11. **Tendon Insertion Strain**

Pain at the base of the fifth metatarsal bone may be caused by insertion strains of the tibialis posterior or peroneal tendon, often following a severe inversion or eversion strain (Williams & Sperryn, 1976).

**Additional Conditions**

12. Chilblains  
13. Deep vein thrombosis in plantar veins of the foot  
14. Diabetes mellitus and peripheral vascular diseases  
15. Gout  
16. Heel spur syndrome  
17. Ischaemia  
18. Localised abscess  
19. Oedema (e.g. varicose veins)  
20. Osteomyelitis  
21. Paget's disease
22. Periostitis
23. Rheumatoid arthritis
24. Tumours (primary or secondary)
25. Verrucae
SUMMARY OF THE LITERATURE REVIEW

Since 1979 Liquid Crystal Thermography (LCT) has been widely used, particularly in America, to diagnose and monitor many diseases and injuries. These have included cancer, back conditions, circulation problems and overuse conditions.

However, it can be concluded from the literature review that despite the many factors which can influence the accuracy of LCT (Lewit et al., 1982, Henahan 1982, Wexler 1981) no studies have been reported with respect to methodology. A basic methodology is outlined in numerous articles (Wexler 1981, Pochaczevsky 1983) but this is not supported by reliable, objective research. It would appear therefore that this may be a major cause of rejection of LCT as a viable technique in Britain (Clarke 1982).

The major factors that require such an approach can be divided into two areas: those concerned specifically with the behavioural properties of liquid crystal and those that interact between the liquid crystals and the patient. The former comprise the camera angle which is used to photograph liquid crystals and the care of the liquid crystals. The latter encompass the time required to stabilize the patient's skin, the effect of pressure and spread plus fade on the thermal image (the degree of photographic delay after patient contact) effects and the natural condition of the patient's skin.

The photographic angle (camera to crystal sheets) is not defined in the literature which could cause problems in interpretation of results. Although the camera is, in most studies, in a frame that maintains it at the same angle for each photograph, the reason for this in relation to viewing angle and rotation of the liquid crystals is not stated.
The care of liquid crystal sheets is not mentioned in any of the literature despite the fact that the sheets can show degenerative changes with exposure to ultra violet light and general mishandling (Edmund Scientific 1980). Such changes could affect the accuracy of the thermograms taken over an extended period of time.

Suggestions for stabilisation of patients' skin temperature range from 2-20 minutes and include the use of fan coolers to lower skin temperature (Pochaczevsky 1983, Rubal et al., 1982, Sandler and Martin 1985). There is no uniform method in successive studies. It would therefore seem that to achieve reliability in the usage of LCT requires the establishment of a standard stabilisation period.

To aid accurate results it is necessary to ascertain whether the image produced on the thermogram corresponds to the area of the body part (ie foot) being viewed, and whether the amount of pressure applied by the body part affects the thermogram. If the image has spread or if changes in colour have occurred in response to varying degrees of pressure this may lead to difficulties in interpretation. 'Hot spot' areas may be misleading and may not be an accurate representation of the skin area under observation. Objective testing is required to determine the effect of these factors stated above.

The degree of photographic delay (fade) after the application of the liquid crystals to the skin does not seem to have been considered and varies with each system: for example when the crystal sheet is in contact with the skin (Tonegutti et al., 1980) or when there is a time lapse of several seconds after its removal (Pochaczevsky 1983). Due to these discrepancies the reliability of LCT must be questioned if the fade of the thermogram is alinear. This aspect is not considered in any of the literature reviewed.
The condition of the skin and treatments that may affect the distribution of temperature and therefore the thermogram, are randomly mentioned with reference to the use of air coolers on moist skin and to the observation that the effect of hot and cold packs disappears after approximately 45 minutes (Wexler 1981). However, the differing aspects of wet or dry skin have not been investigated. Further, it is noted that abnormal temperature patterns caused by hot and cold packs return to normal after a given time, but the period of exposure itself is not stated. Reference is made in the literature to inaccuracies resulting from the use of creams, rubbing etc., (Wexler, 1981) but these again are not defined. Such factors could cause major problems both in terms of reliability and of interpretation and could lead to false positive and negative results.

The literature review introduces a new, inexpensive, non-invasive technique that can be used for the diagnosis and monitoring of disease and injury. However, the technique of application and general methodology give rise to doubts concerning accuracy and reliability in the clinical situation. It must be noted that liquid crystals are a non-specific indicator of temperature increase and that 'hot spots' may be due to several different causes. It can therefore not be used alone in diagnosis or monitoring but must be considered in conjunction with other clinical techniques. If LCT is to be a successful aid in the medical field the above mentioned factors need to be tested objectively and documented in order to dispel doubts about both its accuracy and reliability. This could lead to a reduction in false positive and negative results recorded in the literature and to a wider acceptance of this technique.
9. The Basis of the Research Programme

Liquid crystals, encapsulated in a plastic sheet, have a clear potential for use in the medical field. They provide a method of determining human skin temperature, and therefore inflammation, and are inexpensive, non-invasive and are reusable. Liquid crystal technology has been widely used in America but has failed to gain acceptance in Britain due to doubts concerning accuracy and reliability. No research appears to have been conducted into the basic factors that can effect thermograms, and a definitive methodology has yet to emerge.

The basis of this study is therefore, to determine the behavioural characteristics of liquid crystals in relation to their method of use in monitoring human skin temperature. This research programme investigates the most appropriate medical application of liquid crystals, particularly in the area of sports injuries and overuse conditions of the foot. The foot is chosen for this study due to the variety of conditions that occur in this structure and to its high degree of contact with the liquid crystal sheets. In addition, the foot can be stressed with exercise to reveal pressure areas.

The study consists of a main experimental section, divided into five separate experiments. The aim of this section is to determine the factors that may affect the use of liquid crystals and subsequently define the method of application. The uses of liquid crystal thermography in the clinical situation are illustrated in Appendix 1.

The factors examined in section 2 are the camera angle used to photograph liquid crystals, the care of the liquid crystal sheets, stabilization of patient’s skin, the effect of pressure and spread and fade on the thermal image, and the effect of skin condition on the thermogram. Any of these
factors may affect the reliability of the liquid crystals and the subsequent interpretation of results and need to be investigated before a definitive methodology can be established.

In Appendix 1 cases are examined of both normal and abnormal feet after stabilization, but in unspecified ambient temperatures. The thermal patterns after exercise are also considered.
2.1 PHOTOGRAPHY OF LIQUID CRYSTALS

2.1.1 Introduction

It was important to establish the technique of photography of the liquid crystals before experiments involving photography of the sheets were carried out. However, this photographic technique was not developed in formal experiments but as a continuing analysis of photographic results and improved photographic knowledge. This 'experiment' is therefore divided into sections detailing progressive developments resulting in the establishment of the final technique.

Grabmaier (1975) states the importance of a constant viewing angle when using liquid crystals in being not only a function of the angle of incidence of light, but also of the viewing angle of the scattered light. This factor would apply whether viewing the crystals with the naked eye or during photography. He also states that the colour changes are best photographed by illuminating the crystal surface with a strong light source about 1 m from it. In addition he suggests the use of a polarizing filter on the camera lens to reduce surface reflection.

Kodak (1982) advise the use of a flash unit to produce a light source for the photography of liquid crystal sheets and also to keep extraneous light down to a minimum to prevent shadow.

From the literature review of the clinical use of liquid crystals, photographic technique is not detailed, although much of the photography is carried out within a fixed frame (Pochaczevsky 1983). However, there is no reference in these studies to reasons for constant camera angle, fixed lighting, etc. The photographic technique of the liquid crystals where the frame is not in use is not described in the literature.
2.1.2 MATERIALS

PHOTOGRAPHIC EQUIPMENT

(i) To obtain a permanent record of the thermal images, produced on the liquid crystals, photographs were taken using a Chinon CM-4 35 mm single lens reflex camera.

(ii) A constant light source was provided using a Prinz Jupiter 577 CB computerised electronic flash unit.

(iii) To reduce the glare caused by the flash light on the highly reflective surface of the liquid crystals, a tissue diffuser was applied over the flash unit.

(iv) To further minimise flare, a Hoya polarizing filter was fitted to the camera lens. A Hoya +1 Diopter filter was also fitted to the camera lens to enlarge the photograph of the thermal image to aid interpretation.

(v) The camera and flash were mounted on a standard photographic tripod, allowing adjustment of height and camera angle.

(vi) 3M (Minnesota Mining & Manufacturing Company, St. Paul, Minnesota, U.S.A.) Colour print film was used (135, A.S.A. 100, DIN 21).

(vii) A Kodak Colour Patch (B.S. 3020) was incorporated within the photograph to aid standardisation of colours during development.

2. Liquid Crystals

To obtain thermal images, encapsulated sheets of cholesteric liquid crystals were used. These crystals are
finely dispersed within a polymer matrix and are backed with Mylar (trade name for polyethylene glycol terephthalate). Changes in temperature affecting the sheet cause alterations in the molecular structure of the crystals and the resulting shift is seen as iridescence, due to the reflection of light by the crystals. (See Section 1.2). The sheets for this study were supplied by Davis Liquid Crystals (San Leandro, California, U.S.A.). The sheets measure 15.2 cm (6") x 30.5 cm (12"). (Smaller sample sheets of 10.5 cm x 16 cm were used in initial experiments). The sheets were supplied in three temperature ranges 20°C-25°C, 25°C-30°C, 30°C-35°C.

A liquid crystal sheet was mounted on to a wooden base as illustrated in figure 11 and changed as sheets with different temperature ranges were required.

2.1.3 METHODS

SECTION 1

(i) The camera was placed on the tripod, horizontal to the liquid crystal sheet (see fig. 12). The light source was supplied by daylight. No filters were added to the lens of the camera, 100 A.S.A. Colour print film was used. A camera speed was set at 1/60 second and the aperture at f 1.9.

(ii) Discussion

The light source provided by daylight showed too much variation and also caused patches of shadow. The developed photographs needed a colour patch (Kodak) to provide consistency of colour. The actual image produced needed some enlargement to aid interpretation.
Fig 11 Layout of mounted liquid crystals

- Kodak colour scale
- Heat/colour scale
- Sheet to cork backing
- Sheet
- Drawing pins to secure

- Wooden base
- Insulation
- Cork layer for
details of prints
- Plastic sleeves for
Fig 12. Position 1 of photographic equipment

Fig 13. Position 2 of photographic equipment
SECTION 2

(i) The camera and tripod were assembled as in section 1. A +1 diopter filter was fixed to the camera lens to provide magnification of the thermal image. A Kodak colour patch was placed alongside the liquid crystal sheet (see fig. 11).

The light source was provided by a spot lamp (Reflector Spot 100W) at 45 cm in height and at an angle of 45° to the sheet. The distance from the spotlight bulb to the centre of the sheet was 1 m. (see fig. 13)

(ii) Discussion

The heat emitted from the spotlight bulb produced a colour change to the liquid crystal film and could not therefore be used. The camera angle would need to be changed to allow a subject's feet to be placed on the liquid crystal sheet.

SECTION 3

(i) An electronic flash unit was placed on the camera and set to a distance of 1 m. The aperture of the camera was set of 5.6. The camera was tilted to an angle of 15° to allow a subject to place his/her foot on the crystal sheet. (see fig. 14a).

(ii) Discussion

The flash unit provided an even light source but flare was caused on the developed photograph due to light reflection. A black cardboard surround was needed under the hardboard platform to provide a consistent background.
Fig 14a Position 3 of photographic equipment

Fig 14b Final position of photographic equipment
(i) The final position of the photographic equipment was established and is detailed in fig. 14b. A polarizing filter was added to the camera lens and a tissue diffuser to the flash unit to reduce glare. Extraneous light was kept to a minimum and can be achieved in the clinical situation by turning off lights and/or drawing blinds or curtains.

(ii) Conclusion

This photographic technique was therefore adopted for all subsequent experiments and encompasses the criteria suggested by Grabmaier (1975) and Kodak (1982). The assembly of the equipment is simple and the photographic images produced are consistent in colour and have minimal flare (caused by the reflective surface of the liquid crystals).
2.2 STOR AG E AND USE OF LIQUID CRYSTALS

2.2.1 Introduction

Davis (1982), states that liquid crystal film degrades in U.V. light, and that excessive exposure results in a downward shift in the films of 1°C or more i.e. colour registers 1°C below the stated range of the film. If storage is not checked and parts of the film are left exposed to U.V. light, interpretation of thermal images may be unreliable. The object of this experiment was to determine whether L.C. film exposed to U.V. light changes its temperature indicating range.

2.2.2 Materials

1. Environmental Chamber

To control ambient temperature during experiments in Section 1, the experiments were conducted in an environmental chamber. The accuracy of the chamber was to ± 0.5°C with a human subject in the chamber and to ± 0.1°C when the chamber was empty. The temperature and humidity equipment was manufactured by Techtronics.

Temperature and humidity were measured by sensing probes within the chamber and in the inlet duct and were recorded on a Chessell Chart Recorder (320).

2. Photographic Equipment

(i) 35 mm single lens reflect camera - Chinon CM-4
(ii) Additional filters: Hoya polarizing filter
     Hoya +1 Diopter filter
(iii) Computerised electronic flash unit - Prinz Jupiter 577 CB
(iv) Standard photographic tripod
3. **Liquid Crystals**

Encapsulated sheets of cholesteric liquid crystals supplied by Davis Liquid Crystals were used in this experiment (refer to 2.1.2 (2)).

4. **Metal Weight**

An even area of pressure was applied to the liquid crystals using a 100 gram cylindrical weight taken from a laboratory weight set. The surface area was 280 mm².

5. **Water Bath**

In order to heat the 100 gram weight to the required temperature a water bath was used manufactured by Tecam. To check the water temperature a standard thermometer measuring in °C and accurate to ± 0.5°C was inserted in the water bath.

2.2.3 **METHODS**

1. **Environmental Chamber**

The chamber was set at a temperature of 22°C and a humidity level of 55%. This temperature was selected to be below the range of the liquid crystal film being used, so that a change in colour of the film, caused by the temperature in the chamber, did not occur. The temperature and humidity represented the average conditions found in consulting rooms.
2. Photographic Equipment

The equipment was assembled as shown in fig. 14b (refer back). The camera angle was set at a constant 15° and reasons for this are discussed in the following experiment. A camera speed of 1/60 second was used and an aperture of f5.6. The flash unit was placed parallel to the axis of the lens and set at a distance of 1.2 metres from the liquid crystal plate.

3. Liquid Crystals

The range of the film used in this experiment was 25°C-30°C. Two sheets of liquid crystal film measuring 15.2 cm x 30.5 cm were placed side by side as shown in fig. 15. Sheet (2) was first used in 1981 and had not been uniformly protected during storage. It can therefore be stated that this sheet had, either in part, or as a whole, been exposed to prolonged periods of ultra-violet light. Sheet (1) (1984) had been correctly stored since manufacture (Davis 1982) and had therefore had minimal exposure to ultra-violet light.

A colour scale was placed alongside the liquid crystal film as visual results are important. The scale corresponds to the colours that can be produced by applying increased temperature to the film - brown being the coolest and blue the hottest temperature represented.

4. Weight

The metal weight was placed in the water bath which was filled to the recommended level with water. The thermometer was also inserted in the water bath to check the water temperature and therefore the temperature of the weight. The temperature of the water was set to 27°C.

2.2.4 Methodology

All materials were placed in the environmental chamber for
Fig 15  Layout of 1981 and 1984 Liquid Crystal Sheets
1 hour to stabilise.

1. The metal weight was heated, removed from the water bath, dried and placed immediately on to the 1981 sheet (2). The position was maintained for 1 second, after which the weight was removed and the thermal image immediately photographed.

The procedure was repeated for the 1984 sheet (1).

2. The metal weight (after heating and drying) was then placed across the border between the 1981 and 1984 sheets, so that the image was equally divided between the two sheets. This thermal image was then photographed as described above.

The two sections of this experiment were repeated 3 times. In addition, as the basis of this study was to use thermograms to screen the human foot, (ii) was repeated using a subject's foot with the resulting print equally divided between the 1981 and 1984 sheets. A comparison was then made between this result and a thermal image produced in the same way using two sheets of 1984 liquid crystals side by side.

2.2.5 Results

The results of the experiments are presented visually. Those using a metal weight are shown in fig 16 and those using the human foot in fig 17. Detailed analysis was not required as differences were evident from visual inspection of the photographs and similar results were obtained using both the metal weight and the human foot.
Fig 16. Images produced by metal weight
25 °C-30 °C
SHEET 1 - 1981 (exposed to U.V. light)
SHEET 2 - 1984

Fig 17a  Image produced by human foot
Fig 17b  Image produced by human foot using 2 sheets of 1984 liquid crystals
2.2.6 Discussion

From the photographic results of the experiment it can be seen that the 1981 liquid crystal sheet is registering the metal weight at an inaccurately high temperature. The metal weight was heated to 27°C and would therefore be expected to register a green/blue colour on a normal sheet (range 25°-30°C) as shown by the image on the 1984 sheet. However, the 1981 sheet registered a dark blue colour which indicates the temperature of the metal weight to be out of the range of the sheet and therefore >30°C. The statement of Davis (1982) that liquid crystals, subjected to prolonged exposure to ultra-violet light, degenerate to show a shift of 1°C or more and a resultant inaccuracy in readings is therefore shown to be correct. This effect is illustrated initially by using a metal weight and then, during further investigation, using the human foot.

It was also noted from the results, using both the metal weight, and the foot, that the thermal image near the border of the 1981 film was distorted and that a small degree of spread had occurred. This effect was limited, in both experiments, to approximately 0.5 cm. The extent to which this effect progresses with further ageing of the sheets, however, could not be tested.

2.2.7 Conclusion

To achieve reliable results using liquid crystal films, no part of the film should be exposed to prolonged periods of ultra-violet light either during use or during storage. However exposure to ultra-violet light cannot be avoided during the use of liquid crystals for screening and therefore
periodical tests should be made against unused film to monitor any potential deterioration in either the temperature range of the film or the response to temperature at the edge of the film. In addition to this, a diary of usage of the films, which would outline the frequency of use and therefore exposure to ultra-violet light, could be a useful safeguard against inaccuracy.

Should the changes shown in this experiment occur, the film must be discarded as it is no longer accurate for clinical use (for example, if an injury is being monitored over a period of time to show a reduction in inflammation and therefore heat, affected film could give inaccurate thermal images and therefore confuse interpretation).

All film used for screening in the clinical situation should therefore be uniformly covered on both sides when not in use. Davis (1983) suggests that a cardboard sleeve is adequate for this purpose.
2.3 STABILIZATION OF SUBJECTS

2.3.1 Introduction

From the literature review the stabilization time suggested for subjects' skin, ranges from 10-20 minutes (Rubal, et al, 1982, Pochaczevsky, 1983). However, if subjects are screened in the clinical situation, and if results are to be reliable, a stated time for stabilization of subjects' skin must be established. If this is not standardised, discrepancies in interpretation may occur due to inaccurate thermal patterns. In addition, the method of stabilization and exposure or non-exposure of the skin to the environment must be considered.

This experiment was designed to test the pattern of subjects' skin temperature during a stabilization period of 25 minutes with each subject positioned in the same way and with the foot exposed to the ambient environment within a controlled situation. Through subsequent analysis of the data, the establishment of a standard stabilization time for clinical screening, was considered.

2.3.2. Materials

1. Environmental Chamber

Set to a temperature of 22°C and a humidity level of 55% (Refer to 2.2.2. (1)).

2. Thermisters

To measure both metal weight temperature and subjects skin temperature during these experiments, calibrated thermisters manufactured by Edale were used and were accurate to ±0.5°C.
3. **Stopwatch**

A stopwatch manufactured by Heuer produced an accurate measurement of the length of stabilization time and of specific reading times of subjects skin temperature.

4. **Adhesive Tape**

A standard roll of adhesive tape was used to secure thermisters in place on the subjects skin.

5. **Chairs**

Two chairs were placed together in the environmental chamber for subjects to sit on and elevate their legs to the horizontal.

2.3.3 **Methods**

1. **Environmental Chamber**

Set to a temperature of 22°C and a humidity level of 55% (Refer to 2.2.2. (1)). The temperature and humidity levels were selected to be representative of environmental conditions found in most consulting rooms.

2. **Thermisters**

The calibrated thermisters were placed in three positions (see fig 18) on the foot to give an accurate overall reading of temperature of the skin of the subject. Taking a midline lengthways on the foot, one thermister was placed proximal to the metatarsal heads, one proximal to the medial cuniform and one proximal to the calcaneus.

3. **Adhesive Tape**

The thermisters were secured to the skin using small lengths of adhesive tape.
2.3.4 Subjects

Eight subjects were used in this experiment, 3 male and 5 female, taken from University Staff. They were at the time of the experiment, asymptomatic with respect to their feet and had not used any treatments that could affect skin temperature (see section 7). Their physical characteristics are displayed in Table 1.

<table>
<thead>
<tr>
<th>Subject</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>60</td>
<td>53</td>
<td>52</td>
<td>37</td>
<td>27</td>
<td>26</td>
<td>25</td>
<td>24</td>
<td>38.0</td>
<td>13.85</td>
</tr>
<tr>
<td>Weight kgs.</td>
<td>79.3</td>
<td>57.9</td>
<td>66.6</td>
<td>63.4</td>
<td>75.2</td>
<td>78.8</td>
<td>77.0</td>
<td>58.9</td>
<td>69.6</td>
<td>8.4</td>
</tr>
</tbody>
</table>

2.3.5 Methodology

The subject entered the environmental chamber and was seated on one chair. The subject then removed shoes and socks and elevated their legs to the horizontal on the second chair. The thermisters were placed in position on the subject's foot by a technician who then left the chamber. Readings were initiated outside the chamber immediately after the application of the last thermister. Readings were taken every minute from the individual thermisters for a period of 25 minutes. This method was repeated for each subject in a random order for left and right feet.

2.3.6 Results

The graphic representation of the stabilization pattern for an individual used in this experiment is shown in fig 19.
Fig 19 Example of subject stabilization
This shows the temperature over time for the three areas of the foot measured (refer to fig 18). This is given as an example of 8 subjects chosen from University staff. To determine the point in time to take thermal prints, the percentage decrease in temperature for all eight individuals was plotted against starting temperature for the periods 0-10 minutes (fig 20) 0-15 minutes (fig 21) and 0-25 minutes (fig 22). From this data the correlation coefficient, line of best fit and significance of correlation were calculated.

The ideal time to take thermal prints can be stated as that when the percentage decrease in temperature is independent of starting temperature and when all subjects satisfy the definition of stability: Tm range = 0-3 minutes, Tp range = + or - 0.5°C where Tm = time and Tp = temperature. (+ or - 0.5°C was selected as the liquid crystals only react in divisions of 1°C.)

From the data collected from the stabilization of subjects it was observed that for the period of 0-10 minutes the criteria stated was met and there was no significant correlation (r = 0.06 p > 0.05) between starting temperature and percentage decrease of that temperature. For the period 0-25 minutes, there was a significant correlation (r = 0.77 p < 0.001) between starting temperature and percentage decrease. An intermediate time of 0-15 minutes gave a slight significance of correlation (r = 0.38). Therefore the length of time chosen for stabilization was 10 minutes.

Table 2 Time taken for Subjects to Reach Definition of Stability

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>MEAN</th>
<th>STANDARD DEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME IN MINUTES</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>7</td>
<td>1</td>
<td>2.87</td>
<td>2.20</td>
</tr>
</tbody>
</table>
Fig 20 Effect of Starting temperature on % Decrease 0-10 minutes

$r = 0.06$
Fig 21 Effect of Starting temperature on % Decrease 0-15 minutes

$r = 0.38$
Fig 22  Effect of Starting temperature on % Decrease 0-25 minutes

\[ r = 0.77 \]

\( p < 0.001 \)
2.3.7 Discussion

The literature review showed an unacceptable variation in suggested stabilization time for subjects' skin, both in methodology and length of time required. (Rubal et al, 1982, Pochaczevsky, 1983). The object of this experiment was to establish a consistent methodology and, by monitoring the temperature of three points of the foot (refer fig 18), to calculate the ideal time to take thermal prints.

A definition of stability (Tm range = 0-3 minutes, Tp range = + or - 0.5°C) was used which was formulated by taking into account the properties of the liquid crystals, i.e. only registering in 1°C sections. Three minutes was established to give adequate time to take a thermal print after a set temperature was reached.

To obtain reliable thermal images subjects needed to satisfy the definition of stability and the % decrease in the foot was required to be independent of the starting temperature (i.e. that environmental effects on the foot were minimised). For stabilization in excess of 10 minutes significant correlations were obtained between % decrease and starting temperature (0-15 minutes, r=0.38, p<0.05; 0-25 minutes, r=0.77, p<0.001). For the 0-10 minute period however, the % decrease in the foot temperature was independent of the starting temperature (r=0.06, p>0.05). Therefore the length of time chosen for stabilization was 10 minutes.

2.3.8 Conclusion

The subjects for this experiment were monitored in environmentally controlled conditions that would, in most cases, represent the conditions found in a doctor's surgery. Through analysis of results 10 minutes was found to be the ideal period of stabilization before thermal prints are taken. The 10 minute stabilization period with the subject barefoot and with legs elevated to the horizontal was therefore implemented in further experiments before taking thermal prints.
2.4 THE EFFECT OF PRESSURE, SPREAD AND FADE ON THE THERMOGRAPHIC IMAGE

2.4.1 Introduction

Liquid crystal thermography has been used extensively for measuring human skin temperature to detect abnormalities. However, the effect of the application of the crystal to the skin, together with resultant image, have been ignored and require investigation if reliable and repeatable methods are to be established.

Although methodologies are different for testing any potential effects of these factors, the requirements or apparatus and methods are common and therefore the effects of pressure, spread and fade are considered together below.

(i) Pressure

If L.C. produce an image that is dependent on the pressure applied to it by the skin, and if 'hot spots' appear on the thermal image as a result of such increased pressure, then the use of thermography to detect abnormal heat patterns must be questioned. Thus the first hypothesis to be tested was that the thermal image produced is independent of the applied pressure.

(ii) Spread

If a thermal image does not match the area of the body part being screened this could lead to problems of interpretation. Thus, the hypothesis for this experiment is that there is no spread of the thermal image, and that this is independent of the length of contact time.
(iii) **Fade**

If the rate of fade of the thermal image is linear, the degree of photographic delay after the removal of the body part from the crystal plate, is less critical. However, the delay time before photography of the image must be standardised for each subject screened. In addition if a body part only registers in the cooler range of colour on the L.C. film the image will fade much faster than if the hotter colour range has been reached. In this case immediate photography may be necessary.

2.4.2 **Materials**

1. **Environmental Chamber**

   Set to a temperature of 22°C and a humidity level of 55%. (Refer to 1.2.2. (1).

2. **Photographic Equipment**

   (i) 35 mm single lens reflex camera
   (ii) Additional lens
   (iii) Flash unit (with light diffuser)
   (iv) Photographic tripod
   (v) 3M Colour print film
   (vi) Kodak Colour Patch
   (Refer to 2.1.2 (1)

3. **Liquid Crystal Sheets**

   Encapsulated sheets of cholesteric liquid crystals. (Refer to 1.1.2 (2)
4. Metal Weight

(Refer to 2.2.2 (4)

5. Water Bath

(Refer to 2.2.2 (5)

6. Thermisters

(Refer to 2.3.2 (2)

7. Stopwatch

(Refer to 2.3.2 (3)

8. Loading Rig

To apply known pressure to the liquid crystal sheets using the metal weight (4) a loading rig was constructed (See fig 23). Standard disc sport weights were used in this rig, manufactured by Weider (1 kg, 2.5 kg, 5 kg). A pedestal was placed underneath these weights (see fig 23) which in turn fitted over a metal rod (diameter 1 cm) using a wooden ring. The rod could slide within a metal sleeve supported by clamps. A cork was fitted to the base of the metal rod and the centre was hollowed out to allow insertion of thermister.

2.4.3 METHODOLOGY

1. PRESSURE

All materials were stabilized in the environmental chamber for 1 hour. The 100 g weight (as shown in fig 23) was heated by immersion in the water bath, to a temperature of 27°C. It was removed, dried and immediately inserted into the cut out
Fig 23 Loading Rig

weight

wooden pedestal fitted over metal rod

metal tube (sleeve) diameter 1.2 cm

metal rod diameter 1 cm

30 cm 20 cm clamps

cork

temperature sensor

Hollowed out centre of cork to allow insertion of temperature sensor and weight

metal weight (100 g)

liquid crystal sheet
(i) 100 g

The heated 100 g weight and cork (without additional weights) were then applied to the liquid crystal sheet. The weight was lowered to rest on the sheet for 3 seconds, was then removed and the resulting image immediately photographed.

(ii) 1 kg

The method was repeated as above but the apparatus shown in fig 23 was tested to allow the application of additional weight. The 1 kg weight was placed on the pedestal. The apparatus was then applied to the sheet and upon removal was swung away to allow photography of the image.

(iii) 5 kg

As above, using a 5 kg weight placed on the pedestal.

The entire experiment (i-iii above) was then repeated and the resultant images compared visually for indications of differences in colour and therefore effects of pressure.

2. SPREAD

The 100 g weight was heated to 30°C by immersion in the water bath, and applied to the liquid crystal sheet as above. This was repeated using the 1 kg, 2.5 kg and 5 kg weights. However, in these experiments the weights were left in place on the sheet for 30 seconds before removal and immediate photography. This procedure was repeated and the diameters of the resulting photographic images were measured using standard measuring dividers and a ruler marked in millimetres.
3. **FADE**

The 100 g weight was heated to 30°C by immersion in the waterbath and again applied to the crystal sheet as described in the experiment on pressure. On removal of the weight the resulting image was photographed at intervals of 1, 5, 10, 15, 20 and 25 seconds. This was repeated with the 1 kg, 2.5 kg and 5 kg weights. The complete experiment was performed twice and the diameters of the photographic images measured in millimetres.

2.4.4 **Results**

The results of the experiment on pressure are displayed visually whilst those on spread and fade are presented graphically. The data obtained from the experiment on spread did not require further analysis, however, for the experiment on fade, the data was analysed by determining the line of best fit and the correlation coefficient of fade time and diameter of the image. In addition an analysis of variance was undertaken.

**Presentation of Data**

**Pressure**

A typical example of the thermal images produced during one of the three replicated experiments is shown in fig 24a. The results indicated that the image produced is independent of the pressure applied, this being the case for all results.

**Spread**

The data obtained on the effect of spread using 100 g, 1 kg, 2.5 kg and 5 kg weights are shown in fig 24b and indicate that there was no spread of the thermal image with respect to
Fig 24a Effect of pressure
Fig 24b Effect of spread on the thermal image. Diameter (mm)

Time (seconds)

100 g

1 kg

2.5 kg

5 kg
either the contact time or the pressure being applied and therefore no further analysis was undertaken.

Fade

Table 3 shows the data from the experiment on fade and indicates a linear decrease in the diameter of the thermal image with time. The data are also presented graphically in figs 25a-d together with the line of best fit and the correlation coefficient.

An analysis of variance was also carried out to determine the effect of increased weight on the pattern of fade (Table 4). From the results it was shown that the effect of increased weight did not have a significant effect on the pattern of fade (p > 0.050).

2.4.5 Discussion

Pressure

The hypothesis, to be tested in this experiment, that the thermal image is independent of the applied pressure, was accepted. The thermal images produced after the application of increased weight (up to 5 kg) showed no differences in colour and therefore temperature. If the application of increased pressure over an area on the thermal image produced a change in colour and therefore an increase in temperature then liquid crystal thermography would be shown to be an unreliable method of illustrating a thermal pattern and interpretation would be difficult.

Spread

The hypothesis for this experiment was also accepted. That is that no spread of the thermal image was detected over
Table 3 Raw Data Fade (Diameter shown in millimetres)

<table>
<thead>
<tr>
<th>TIME WEIGHT</th>
<th>100 g</th>
<th>1 kg</th>
<th>2.5 kg</th>
<th>5 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 s</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
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<tr>
<td></td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>5 s</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
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<tr>
<td></td>
<td>4.0</td>
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<tr>
<td></td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>10 s</td>
<td>3.5</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>3.5</td>
<td>4.0</td>
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<tr>
<td></td>
<td>3.5</td>
<td>4.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>15 s</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
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<tr>
<td></td>
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<td>3.5</td>
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<tr>
<td>20 s</td>
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<td>3.0</td>
<td>3.5</td>
<td>3.5</td>
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<tr>
<td></td>
<td>3.0</td>
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<td></td>
<td>2.5</td>
<td>3.0</td>
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<td>3.5</td>
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<tr>
<td>25 s</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
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<td>2.5</td>
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<td></td>
<td>3.0</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Fig 25a Effect of fade on the diameter of the thermal image 100 g.

\[ R = -0.917 \]
\[ y = -0.123x + 5.045 \]
Fig 25b Effect of fade on the diameter of the thermal image 1 kg

\[ R = -0.96 \]

\[ y = -0.112x + 4.92 \]
Fig 25c Effect of fade on the diameter of the thermal image 2.5 kg

$R^2 = -0.94$

$y = -0.08x + 4.67$
Fig 25d: Effect of fade on the diameter of the thermal image 5.0 kg

\[ R = -0.96 \]
\[ y = -0.082x + 4.69 \]
Table 4: Analysis of Variance for Experiment on Fade to

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>D.F.</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>75.790</td>
<td>7</td>
<td>10.820</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Weight</td>
<td>30.292</td>
<td>1</td>
<td>30.292</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2-Way Interaction</td>
<td>5.989</td>
<td>1</td>
<td>5.989</td>
<td></td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Residual</td>
<td>0.476</td>
<td>54</td>
<td>0.009</td>
<td></td>
<td>0.778</td>
</tr>
</tbody>
</table>

Total 33.819

Notes:
- 72 cases
- Determine effect of weight over time
- Analyze the variance for Experiment on Fade to
time for up to 30 seconds of contact and for contact weights of up to 5 kg. The interpretation of the thermal image can therefore be undertaken with the knowledge that the thermal image produced is of the same dimensions as the object or skin area being studied and in contact with the liquid crystal sheet. It should be noted however, that in the experiment on the storage and use of liquid crystals (2.2), a small degree of spread occurred near the border of a sheet of liquid crystals which were manufactured in 1981 and which had been exposed to ultra violet light. This emphasises the need to store liquid crystal sheets correctly.

**Fade**

The pattern of fade of the thermal image appeared to be linear against time and from the results and the analysis of variance there was no significant difference in the pattern of fade with time for weight between 100 gms and 5 kg. The photographic image could, therefore, in theory, be taken between 0-25 seconds after the metal object or the subject's foot had been removed from the liquid crystal sheet. However as not all the area of the object or skin area screened will always be the same temperature some sections will fade more quickly than others and brown area (cool) may fade within the first seconds. Therefore to accommodate all parts screened it was decided to photograph the image immediately on removal of the object or human foot.

2.4.6 **Conclusion**

**Pressure**

The hypothesis for this experiment that increased pressure applied does not affect the thermal image, was accepted.

**Spread**

Spread does not occur on the thermal image after contact
with a metal object or human skin areas. Area of heat or cold on the thermal image accurately correspond to the areas being screened (refer 2.2). However, it is noted, that films which have been stored incorrectly may be affected and that spread may occur on liquid crystal sheets which have been exposed to ultra violet light.

Fade

The thermal images produced in this study were photographed immediately after the removal of the metal object or human foot because of potential problems caused by fading images.
2.5 The Effect of Skin Condition on the Thermogram

2.5.1 Introduction

The effect of introducing factors that may change the surface skin temperature and therefore the thermogram are discussed in the literature review (Refer 7 Factors that may affect the thermographic pattern). Clark (1982) suggests the importance of recent patient history to eliminate factors such as the recent use of ointments, hot and cold packs or drugs and Wexler (1981) suggests the use of a hair dryer to dry damp or wet skin caused by sweating. However, the natural condition of the skin and the differences that this may have on the thermal image is not discussed in the literature. The skin of the foot is particularly prone to excessive moisture due to sweating in some individuals and it is this factor and its possible effect on the thermogram that is considered in this experiment.

A visual study is made between thermal images produced with dry and wet skin, and a comparison of area of print is made between dry and wet prints and an ink print of the same foot to see if spread is occurring on each of the thermal images.

If the hypothesis that the thermogram is not affected by skin condition is accepted then the area comparison can be used to confirm the results of the experiment on spread (2.4).

2.5.2 Materials

1. Environmental Chamber

Set to a temperature of 22°C and a humidity level of 55% (refer to 2.2.2. 1).
2. Photographic Equipment

   (i) 35 mm single lens reflex camera  
   (ii) Additional filters  
   (iii) Flash unit (with light diffuse)  
   (iv) Photographic tripod  
   (v) 3M Colour print film  
   (vi) Kodak Colour Patch

   (Refer to 2.1.2. 1).

3. Liquid Crystal Sheets

   Encapsulated sheets of cholesteric liquid crystals (Refer to 1.1.2. 2).

4. Water Bath

   (Refer to 2.2.2. 5).

5. Ink Pad Tray and Black Ink

   An ink pad was constructed as shown in fig 26. This was used to ink the subject’s foot prior to producing an ink print on paper.

6. A4 Paper

   Standard quality A4 paper was used for ink prints of the foot.

7. Cotton Wool

   Cotton wool was used to wet and wipe dry the subjects’ feet.
Fig 26  Ink pad

Black ink dripped on to pad

Cloth covered sponge pad

Plastic tray

300 cm

150 cm
8. Weighing Machine

A Sartorius 2001 MV 2 weighing machine was used to weigh the prints and therefore compare area. The machine was accurate to 0.1 mg.

2.5.3 Methodology

The following table was implemented to give random sampling of the subjects' ink, wet and dry prints to prevent a possible overlap effect from any one condition always preceding another.

<table>
<thead>
<tr>
<th>SUBJECT 1</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBJECT 2</td>
<td>C</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>SUBJECT 3</td>
<td>B</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>SUBJECT 4</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>SUBJECT 5</td>
<td>C</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>SUBJECT 6</td>
<td>B</td>
<td>C</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 5 Random Order of Prints

In addition, the right and left foot were alternated with each subject.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>MEAN</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE (YEARS)</td>
<td>53</td>
<td>37</td>
<td>27</td>
<td>26</td>
<td>26</td>
<td>24</td>
<td>32.16</td>
<td>10.22</td>
</tr>
<tr>
<td>WEIGHT (KGS)</td>
<td>57.9</td>
<td>63.4</td>
<td>75.2</td>
<td>78.8</td>
<td>76.1</td>
<td>58.9</td>
<td>68.3</td>
<td>8.55</td>
</tr>
</tbody>
</table>
The subjects were taken from university staff and had, at the time of the experiment, asymptomatic feet.

**Subject 1**

Subject 1 entered the environmental chamber and was seated on one chair. The subject then removed shoes and socks and elevated their legs to the horizontal on a second chair. The individual remained in this position for 10 minutes to stabilize. After this period of time the subject stood up, placed the right foot on the ink pad, removed it and stepped on to the A4 paper. The subject then removed their foot from the paper and was reseated. The resultant ink print was immediately photographed. The technician then carefully wiped the inked foot with cotton wool moistened with water at room temperature to remove the ink. (Excessive wiping was avoided to prevent a skin temperature increase due to friction). The clean skin was re-moistened with room temperature water, the subject stood up and placed their foot on the liquid crystal sheet for 3 seconds. This time span was chosen to allow a subject to correctly position the foot and balance while preventing the temperature raising effect of insulation between the foot and the plastic film. On removal of the foot from the sheet the resultant image was immediately photographed. The subject was reseated and the technician carefully dried the foot using cotton wool. The subject then stood once again placing the right foot on the liquid crystal sheet for three seconds. On removal of their foot from the sheet, the image was immediately photographed.

**Subject 2**

Subject 2 entered the environmental chamber and was stabilized for 10 minutes (refer to subject 1). After this period of time the seated subject stood up and placed their left foot on the liquid crystal sheet. They then removed their
foot and the thermal image produced was immediately photographed. The standing subject then placed the left foot on the ink pad and on to a sheet of A4 paper. The subject was reseated after the removal of their foot from the paper and the ink print was photographed. The technician proceeded to wipe clean the subject's foot with cotton wool moistened with room temperature water. The foot was then moistened again with clean room temperature water. The subject stood up and placed their left foot on the liquid crystal sheet. On removal of their foot, the resulting thermal image was immediately photographed.

Subject 3

Subject 3 entered the environmental chamber and was stabilized for 10 minutes (refer to Subject 1). The technician moistened the subject's foot with room temperature water by wiping the foot with wet cotton wool. The subject then stood up placing the right foot on the liquid crystal sheet. They removed their foot and the image was immediately photographed. The subject was reseated and the technician dried the foot by wiping it carefully with cotton wool. The subject stood up and placed the dried right foot on the liquid crystal sheet. Following removal of the foot from the liquid crystal sheet the image was immediately photographed. The subject then placed the right foot on the ink pad and on to the A4 paper and the resultant ink print was photographed.

Subject 4

The method was followed as for Subject 1 but the left foot was used for the prints.

Subject 5

The method was followed as for Subject 2 but the right foot was used for the prints.
Subject 6

The method was followed as for Subject 3 but the left foot was used for prints.

The films were developed and the resulting ink and thermal print areas were cut out (as shown in fig 27). The prints were cut to the metatarsal heads due to the irregularities of the individual toe prints. The areas of the prints were calculated by the weighing of the cut prints.

2.5.4 Results

The areas of the thermal prints were calculated and are illustrated in Table 7. Paired T tests were carried out to determine whether there were significant differences in the area of the ink wet and dry prints. The results are displayed in Table 8. The differences in area were not significant. The visual results of this experiment are illustrated in Fig. 28 and show the same basic heat pattern for wet and dry skin conditions.

2.5.5 Discussion

This experiment was essentially designed to test the effect of wet and dry skin on the area of a thermal print of the human foot and to compare this with the control supplied by an ink print of the same foot. However the results also consolidated the conclusion drawn from the experiment on spread.

From the result of the experiment it can be seen that natural differences in skin conditions do not affect the thermal image either visually in terms of temperature differences or in terms of significant differences in area of the print. In addition the area of the thermal print was not
Fig 27 Cut areas of prints

Fig 28 Comparisons of wet and dry skin patterns
### Table 7: Area of Prints

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>INK</th>
<th>WET</th>
<th>DRY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.72 cm²</td>
<td>10.46 cm²</td>
<td>9.51 cm²</td>
</tr>
<tr>
<td>2</td>
<td>8.27 cm²</td>
<td>7.85 cm²</td>
<td>8.27 cm²</td>
</tr>
<tr>
<td>3</td>
<td>8.27 cm²</td>
<td>8.64 cm²</td>
<td>8.89 cm²</td>
</tr>
<tr>
<td>4</td>
<td>9.92 cm²</td>
<td>10.13 cm²</td>
<td>9.72 cm²</td>
</tr>
<tr>
<td>5</td>
<td>12.82 cm²</td>
<td>13.23 cm²</td>
<td>12.82 cm²</td>
</tr>
<tr>
<td>6</td>
<td>12.82 cm²</td>
<td>13.65 cm²</td>
<td>12.40 cm²</td>
</tr>
</tbody>
</table>
Table 8 Paired T-Tests to Determine the Different Effects of Skin Condition and Area

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>MEAN DIFF</th>
<th>T</th>
<th>SIGNIFICANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 + 3</td>
<td>0.035</td>
<td>0.24</td>
<td>N/S</td>
</tr>
<tr>
<td>2 + 3</td>
<td>-0.392</td>
<td>1.47</td>
<td>N/S</td>
</tr>
<tr>
<td>1 + 2</td>
<td>-0.357</td>
<td>1.955</td>
<td>N/S</td>
</tr>
</tbody>
</table>

1 = INK
2 = WET
3 = DRY
significantly different from that of an ink print.

**Conclusion**

The patient's natural skin condition, whether it is dry or wet (caused by sweating) does not affect the thermal image in either colour pattern or area. It is not therefore necessary to dry the subject's skin in any way before a thermal image is taken.
The aim of this study was to determine the viability of the use of liquid crystal sheets to study temperature related conditions of the plantar surface of the foot. To achieve this aim an established methodology was required which was based on technical information and an understanding of behavioural characteristics of liquid crystals. Clarke (1982) stated that before the clinical use of thermography progressed too far basic questions concerning thermography needed to be answered. The crystal sheets have been widely used in the U.S.A. but reliable, objective research has prevented their acceptance in Britain for use in the medical field. The review of the literature concerning the use of thermography in areas such as breast cancer detection, back pain, detection of deep venous thrombosis and the use of plastic strip thermometers revealed discrepancies and doubts concerning methodology. Gautherie and Gros (1980) express a clear need to examine methods in order to improve effectiveness in the detection of cancer. Lewit et al (1982) express a clear need to examine methods in order to improve effectiveness in the detection of cancer. Lewit et al (1982) advocate further research and investigation in the use of plastic strip thermometers and Norris (1981) shows concern about discrepancies in methodology when applying thermography to legal cases.

The experimental section of this study was divided into individual parts each dealing with separate but interrelated factors that influenced the eventual methodology. These were the camera angle used to photograph liquid crystals, the care and storage of the liquid crystals, the time required to stabilize the patient's skin, the effect of pressure, spread and fade on the thermal image and the effect of natural conditions of the patient's skin.
Grabmaier (1975) states the importance of a constant viewing angle when observing colour changes in liquid crystals and led to the use in this study of a tripod mounted camera. He also suggested the use of a strong light source to illuminate the crystal surface and the addition of a polarizing filter on the camera lens. The camera angle was therefore established at 15° from the horizontal to allow the correct positioning of the patient's foot and the best light source was found to be a flash unit mounted on the camera at the same angle. The polarizing filter was added to the camera lens and to further reduce glare a tissue diffuser was placed over the flash unit. In addition, a +1 diopter filter was also added to the lens to enlarge the thermal image and therefore aid interpretation. Kodak (1982) suggested the use of a Kodak colour patch placed alongside the liquid crystal sheet to standardize colour reproduction during film development. A hot / cold colour scale was also added alongside the liquid crystal sheet (see fig 1). This technique produced clear photographs with minimal glare.

The importance of the care and storage of liquid crystals is emphasised by Davis (1982) who states that the crystals degrade with exposure to UV light. The experiment reported here compared 1981 film with new 1984 film and found a visual difference between the thermal image produced on each film, supporting the observations of Davis (1982). The 1981 film showed a shift in temperature registration of <+1°C and in addition a small degree of spread was observed at the border of the film. All film should therefore be uniformly covered on both sides when not in use and a diary kept of use and exposure to UV light. This will prevent inaccuracy in interpretation of serial thermograms.

The literature review showed discrepancies in the time allowed to stabilize patients' skin temperature before
screening with liquid crystals. For example Rubal et al (1983) suggested a stabilization time of 20 minutes. In contrast, Pochaczevsky et al (1983) stated 10 minutes to be the ideal time for stabilization. In a later study by Sandler and Martin (1985) a stabilization time of 2 minutes is given, which raises further doubts concerning methodology. Through the monitoring of subjects in an environmental chamber (representing the temperature found in most consulting rooms) and subsequent statistical analysis the results confirmed the findings of Pochaczevsky et al (1983). The starting temperature for all 9 subjects were plotted against the percentage decrease of this temperature for periods of 0-10 minutes, 0-15 minutes and 0-25 minutes. A definition of stability was also applied: Tm range = 0-3 minutes, Tp range = + 0.5°C where Tm = time and Tp = temperature. For the period 0-10 minutes the definition of stability was met and there was no correlation between starting temperature and percentage decrease of that temperature. At 0-15 minutes a weak correlation was observed (r = 0.38) and at 0-25 minutes a significant correlation (r = 0.77 p < 0.001). Therefore 10 minutes was established as the stabilization time for subjects before screening, to minimize the effects of skin cooling.

The effects of increased pressure, spread and fade on the thermal image were not referred to in the reviewed literature. However, it was considered that these factors could affect the reliability and accuracy of the thermal images. The effect of increased pressure on the thermal image was assessed visually and statistically by use of an analysis of variance. Visually there were no differences in the images produced for weights ranging from 100 gms (0.1 kg) to 5 kgs applied to the crystal sheet (pressure equivalent to foot/ground pressures of the human foot, see Morton, 1969). In addition the analysis of variance showed that weight and therefore pressure had no significant effect with respect to the timed application. The images could therefore be interpreted with the knowledge that increased weight/pressure had no effect on the images produced.

A spread of the thermal image on contact with the load, if
it occurred, would affect the accuracy of the thermal image as the resulting image would be different from the area being screened. However, by the application of weights ranging between 100 g (0.1 kg) to 5 kg over periods of up to 30 seconds, no spread was observed. However, a small degree of spread did occur on old, incorrectly stored film as discussed earlier in the experiment on the storage and care of liquid crystals.

The pattern of fade of the thermal image was found to be linear over the first 25 seconds after removal of the part or object being screened. However, to prevent some areas completely fading on the image that had only just registered on the temperature scale, immediate photography of the image was recommended.

Finally in this section the effects of differences in natural skin conditions were considered. Wexler (1981) suggested the use of a hair dryer to dry damp or wet skin caused by sweating. However, if wet and dry skin conditions do not affect the image then this would not be necessary and would avoid the potential problems caused by the resulting skin cooling. Results showed this to be the case through visual comparison of images and paired T tests using the measured areas of wet, dry and ink prints. The ink prints were used as a control and to reinforce the results of the experiment on spread. The results of the paired T tests showed the differences in the area of the prints were not significant.

From the results of the illustrations of normal and abnormal feet screened after stabilization in section 2 of this study, it was realized that the thermal patterns were not always significant enough to indicate specific problems in the athlete's feet. It should be noted that a full patient history is needed to eliminate possible causes of temperature increase caused by drugs or the use of, for example, hot packs (see
section 6 of the literature review). As general indicators of
temperature the crystals were both reliable and accurate
and would be of use in many diagnostic problems, particularly
those of circulation (Richie *et al.*, 1979, Aronen *et al.*, 1980
and Gautherie and Gros, 1980).

However, the images produced from this method did not
always show up smaller areas of heat or cold which would have
been expected from the physical diagnosis. Once the foot had
been stressed by exercise, as suggested by Lockner *et al.*, (1980), some specific conditions became much more apparent and
correlated well with physical findings. It is in this capacity
that the liquid crystals used in this study would be most
effective to diagnose injuries of the athlete's foot.
Conclusion

The following criteria were established through experimentation to improve the accuracy and reliability in the clinical application of liquid crystal thermography.

1. Photographic
   
   (i) Camera - 35 mm Single lens reflex camera. 50 mm lens.
   
   (ii) Filters - Polarizing filter and +1 diopter filter.
   
   (iii) Film - Colour print film. 100 A.S.A.
   
   (iv) Lighting - Electronic flash unit with tissue diffuser
   
   (v) Camera Angle - 15° from the horizontal (Camera mounted on a tripod)
   
   (vi) Kodak colour patch.

2. Materials
   
   (i) No part of the liquid crystal sheet should be exposed to prolonged periods of ultra-violet light either during use or during storage.
   
   (ii) All sheets should be uniformly covered on both sides when not in use.
   
   (iii) Routine checks need to be carried out on the film to assess accuracy and a diary of usage of the sheets should be kept.
3. **Subjects**

   (i) Subjects should be stabilized whilst barefoot and with legs elevated to the horizontal.

   (ii) Stabilization time was established at 10 minutes.

4. **Image**

   (i) Pressure - increased pressure/weight does not affect the thermal image.

   (ii) Spread - does not occur except at the borders of old incorrectly stored sheets.

   (iii) Fade - photographs should be taken immediately after the object or skin area was removed from the liquid crystal sheet to avoid potential problems discussed.

   (iv) Skin condition - the patient's natural skin condition, whether it is dry or wet (caused by sweating) does not affect the thermal image. However, recent applications of, for example cold packs, should be noted before screening.
5. **Application**

The methodology established in the dissertation has resolved many issues relating to the physical properties and use of liquid crystals. It is essential that the criteria used in this study is employed in further research to validate the results and interpretation of the thermograms.

The study has emphasised that the use of liquid crystal thermography is a viable screening technique. Methodology is of vital importance and experimentation has illustrated the factors that can effect results and interpretation. The work carried out here is unique and the resultant methodology incorporates all the factors that could affect the reliability of the thermograms.

Initial thermal images of subjects with symptomatic feet, produced encouraging results, and in addition the feet were stressed by exercise and then screened. Case histories and illustrations of thermographic foot patterns with and without exercise stress are shown in Appendix I. These cases have provided valuable pilot data. More detailed physical and medical examinations and their correlation with the thermograms produced in this study, could be the basis for further investigation with a view to clinical trials (see section 2.8 further research).
This study has investigated the potential of liquid crystal thermography as an indicator of inflammation and consequently injury. The viability of the method has been assessed by investigation of the technical aspects of the liquid crystals. The application of thermography forms a small part of this study and it is in this area of application that requires further research.

Initial thermal images of subjects with symptomatic feet produced encouraging results, but in addition the feet were stressed by exercise and then screened. This method produced better results that correlated well with physical findings. However not all symptomatic feet could be stressed by exercise and guidelines need to be established concerning the exercising or non-exercising of the patient's feet.

A careful and detailed case history of each patient needs to be taken and particular attention given to the recent use of, for example, hot or cold packs. Physical examination (by medically qualified personnel) is required because thermography does not indicate the cause of injury, and the correlation between this and the results of thermal images is of particular importance.

In addition to the application of liquid crystals to the foot and associated conditions, the findings of this study could be applied to other areas of use. These include breast cancer screening, back pain detection and rehabilitation, sports injuries and the detection of D.V.T. It is apparent from the literature review that methodology is not always reliable but if the conclusions reached in this study were considered the use of liquid crystals could become a more accurate and reliable method of skin temperature screening.
REFERENCES

ADAMS, J. Outline of orthopaedics, 9th ed.

Normal footground pressure pattern in children
Clin. Orth. 150: 220

ANON. (1981) International medical news service

of the human body and foot. The foot-ground
pressure pattern
J. Biomechanics 2: 453-457

Thermography in deep venous thrombosis of the leg
Am. J. Radiology 137: 1179-1182

BINDER, A. 1982 (Personal communication - reported by
HENAHAN, J. 1982)

monitoring of skin temperature using a liquid
crystal thermometer during anaesthesia
South Am. Med. J. 71: 516-518

CARPENTER, M. (1982) Thermography is ideal for lower back
pain screening

CLARKE, R. 1982 (Personal communication - reported by
HENAHAN, J. 1982)

CUNNINGHAM, D. Textbook of anatomy. Romanes, G. (Ed)

DAVIS, F. Liquid crystals for thermal non-destructive testing. Davis Liquid Crystals Inc. USA (1967)

DEVAS, M. Stress Fractures.
Churchill Livingston: Edinburgh (1975)

DORLAND, W. Dorland's Medical Dictionary 26th Ed.
W. B. Saunders Philadelphia (1981)

EDMUND SCIENTIFIC Information/Instructions - Liquid crystal Sheets.


Cancer. 45: 51-56

GAUTHERIE, M., HAENDEL, P., WALTER, J. and KEITH, L.
Biomedical Thermography 279-30

Arch. Gen. Psychiatry 35: 1315-1320

J. Am. Med. Assoc 218: 1700-1702

HARRIS, A. Human measurement


Flexitherm News. 2 No. 1 Jan.


JENSEN, C., LOMHOLDT-KNUDSEN, L. and HEGEDIIS, V. (1983)
The role of contact thermography in the diagnosis of deep venous thrombosis
Eur. J. Rad. 3: 99-102

KELKER, H. and KATZ, R. Handbook of liquid crystals
Verlag Chemie: Weinheim (1980)

KLEENERMAN, L. (Ed) The foot and its disorders

KODAK (U.K.) 1984 (Personal Communication)


PARSLEY, M. (Ed) Thermochromic liquid crystals B.D.H. Chemicals, Poole, Dorset 1981


SPENCE, A. and MASON, E. (1979) Human anatomy and physiology Benjamin and Cummings. USA


REFERENCES (ADDENDUM)

MCFADDEN, J. (1983) Thermography used to diagnose the facet syndrome.

NAKANO, K (1984) Liquid crystal contact thermography in the evaluation of patients with upper limb entrapment neuropathies.

Am. J. Pain 20: 293-305

Lancet: March 665-668
The thermographic pattern is illustrated in fig 32 and shows, as with the right foot, an even distribution of heat—"normal" pattern.

DISCUSSION

This case was used as a control with thermographic print taken after the stated stabilization time and after a 10 minu run. The subject's feet were asymptomatic and produced a good illustration of heat patterns of a "normal" foot.
CASE NUMBER: 1

PATIENT DETAILS

MALE FEMALE AGE: 30

SPORT/ACTIVITY: MARATHON RUNNER

RIGHT FOOT

PHYSICAL FINDINGS

Normal

STABILIZATION: FEATURES 20°-25°C SHEET

The thermographic pattern is illustrated in fig 29. The overall pattern of this image is thermographically "normal" and does not appear to illustrate any specific problems.

AFTER RUN (10 MINUTES JOGGING): FEATURES 25°-30°C SHEET

The thermographic pattern is illustrated in fig 30 and shows an even distribution of heat - a "normal" pattern.

LEFT FOOT

PHYSICAL FINDINGS

Normal

STABILIZATION: FEATURES 20°-25°C SHEET

The thermographic pattern is illustrated in fig 31 and shows a slightly cooler temperature than the right foot but still a "normal" pattern.
The main purpose of this study was to determine the viability of liquid crystals as a screening technique. However, the methodology established for the use of liquid crystals was applied to one asymptomatic (as a control) and three symptomatic subjects. This was intended as a pilot study to illustrate the possible applications of the liquid crystal under specified conditions and using the established methodology.

The results of the pilot study were encouraging but further research and medical interpretation is now required (see section 2.8).
APPENDIX I
CASE NUMBER: 2

PATIENT DETAILS

MALE FEMALE AGE: 39

SPORT/ACTIVITY: MARATHON RUNNER

CAUSE OF PROBLEM: RUNNING

RIGHT FOOT

PHYSICAL FINDINGS

These showed a blackened nail and inflammation of the hallux as well as inflammation of 3rd and 5th digits.

STABILIZATION: FEATURES 20-25°C SHEET

The thermographic pattern is illustrated in fig 33 and shows warm areas over the metatarsal shafts and the anterior area of the calcaneum. The narrow lateral border suggests the possibility of excessive foot pronation. However the overall pattern of this image is thermographically "normal" and does not appear to illustrate any specific problems.

AFTER RUN (10 MINUTES JOGGING): FEATURES 25-30°C SHEET

The thermographic pattern is illustrated in fig 34 and shows hot (blue/green) areas at the hallux and to a lesser degree at the 3rd and 5th digits. This represents an abnormal thermographic pattern.

LEFT FOOT

PHYSICAL FINDINGS

These showed blackened nails of the hallux and 2nd digit.
The 3rd digit was slightly inflammed.

STABILIZATION: FEATURES 20-25°C SHEET

The thermographic pattern is illustrated in fig 35 and shows a wider lateral border of the foot which may indicate that less pronation is occurring in this foot than in the right foot. There is also a warm area of the anterior calcaneum. The image is again thermographically 'normal'.

AFTER RUN (10 MINUTES JOGGING): FEATURES 25-30°C SHEET

The thermographic pattern is illustrated in fig 36 and shows hot (blue/green) areas at the hallux and 2nd and 3rd digits. This represents an abnormal thermogram.

DISCUSSION

The thermograms taken after the established stabilization period revealed the possibility of excessive pronation of the right foot. However a biomechanical assessment would be required to confirm this. No specific areas of inflammation were apparent on the thermogram despite positive physical findings of that inflammation. However after stressing the foot through exercise the areas of inflammation found on physical examination were clearly visible on the thermogram.
Fig 33 Case 2 Right

Fig 35 Case 2 Left
CASE 3

PATIENT DETAILS

MALE FEMALE AGE: 18

SPORT/ACTIVITY: SOLDIER RECRUIT

CAUSE OF PROBLEM: 6 MILE RUN (AS PART OF TRAINING)

RIGHT FOOT

PHYSICAL FINDINGS

Normal

STABILIZATION: FEATURES 25-30°C

The thermographic pattern is illustrated in fig 37 and shows a 'normal' pattern of heat.

AFTER RUN (10 MINUTES JOGGING): FEATURES:

Not possible for subject to jog or run due to right foot condition.

LEFT FOOT

PHYSICAL FINDINGS

Blister and inflammation of the skin at the head of the 1st metatarsal. Painful to touch, skin broken.

STABILIZATION: FEATURES 25-30°C

The thermographic pattern is illustrated in fig 38 and shows a diffuse area of heat at and around the head of the
1st metatarsal.

AFTER RUN (10 MINUTES JOGGING): FEATURES:

Not possible for subject to jog or run due to skin state.

DISCUSSION

The thermogram shows a clearly defined area of damage on the right foot caused by rubbing during the run (i.e. ill fitting boots, biomechanical problem). Physical findings are conclusive but thermography could be used in this case to monitor reduction in inflammation.
Fig 37  Case 3 Right

Fig 38  Case 3 Left
CASE 4

PATIENT DETAILS

MALE FEMALE AGE: 17

SPORT/ACTIVITY: SOLDIER (RECRUIT)

CAUSE OF PROBLEM: FELL FROM BUNKER, TWISTED RIGHT ANKLE AND FOOT

RIGHT FOOT

PHYSICAL FINDINGS

Diffuse swelling around the ankle, general tenderness. Also diffuse swelling of the foot especially around the metatarsal shaft area. Suspected metatarsal shaft fracture (3rd/4th met).

STABILIZATION: FEATURES: 25-30°C SHEET

The thermographic pattern is illustrated in fig 39 and shows a warm area at the base of the hallux and a diffuse area over the metatarsal shafts. There is also a hot area over the posterior of the calcaneus.

AFTER RUN (10 MINUTES JOGGING): FEATURES

Not possible for subject to jog/run.

LEFT FOOT

PHYSICAL FINDINGS

Normal
STABILIZATION: FEATURES 25-30°C SHEET

The thermographic pattern is illustrated in fig 40 and shows a fairly even distribution of heat over the foot and a cool lateral border. A thermographically 'normal' pattern.

AFTER RUN (10 MINUTES JOGGING): FEATURES

Not possible for subject to jog/run.

DISCUSSION

The thermograms show a clearly defined injury caused by a fall which did not require exercise stressing, (which in this case would not be possible) as areas of inflammation were clearly defined on the thermogram taken after stabilization. Thermography may be of most use in this case to monitor the reduction of inflammation as physical findings are definite and visible.
Fig 39  Case 4 Right

Fig 40  Case 4 Left