THERMOGRAPHIC STUDIES

OF TISSUE TRAUMA AND SEATING

A thesis submitted to the University of Strathclyde in part

fulfillment of requirements for the degree

of

Doctor of Philosophy

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June 1984

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ABSTRACT

Wheelchair sitters with insensitive skin have a high risk of developing pressure sores. Prolonged pressure produces ischaemic conditions in the underlying tissues which may lead to cellular death and necrosis. Properly designed seating may reduce this risk and prevent the onset of pressure sores. To achieve the best protection possible a method of objective evaluation is required which will account for variations in tissue quality, sitting behaviour and sitting biomechanics.

This thesis reports on the application of thermography into a tissue trauma seating programme and the quantification of isotherm areas for statistical comparisons of skin temperature response to experimental parameters. The thermographic research is presented in three phases of analysis: Chapter 4, a retrospective study of thermograms based on maximum temperatures; Chapter 5 both maximum temperatures from the real-time thermograph display and automatically collected areameter isotherm area data; and Chapter 6, a prospective patient study based on isotherm area data.

During the preliminary stages of research, patients were followed with thermographic examinations at various stages of fitting and trial sitting on wheelchair cushions. There followed a series of tests with able-bodied subjects on experimental seats in an environmental chamber to determine the minimum conditions required for quantitative measurement of thermographic data. The examination room at the Ontario Crippled Children's Centre was then modified accordingly for patient studies and quantitative techniques were tested further. The results of these three phases of reseach are presented with recommendations for continuing studies.

The acquired information supports the use of thermography in tissue trauma programmes. Sites of accumulated stress were found to be identifiable and approaches for the quantitative comparison of thermal response to safe and unsafe loading conditions presented. Maximum temperatures were the most sensitive measures of hyperthermic response and mean imaged temperatures, the most readily characterized for cooling. Detailed discrimination of differences in skin cooling were found to be enhanced when the area of examination was minimized.

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ACKNOWLEDGEMENTS

I must express my appreciation for the support Professor R.M. Kenedi and Professor J.P. Paul have provided during the course of this research. Owing to circumstances of research funding, clinical facilities and instrumentation the clinical research was conducted in extension in Canada but Dr. J.C. Barbenel has provided me with essential guidance in formulating a dissertation out of the general research programme.

The Ontario Crippled Children's Centre, in Toronto, provided institutional support for this programme and fostered an ambience which made it possible to integrate research and service activities. Dr. C.A. McLaurin and later Dr. M. Milner provided local supervision of this research, directors of the Rehabilitation Engineering Department, and I am grateful for their enthusiasm and support. The National Research Council of Canada has made their facilities available to assist in the preparation of this manuscript.

The staff of the Tissue Trauma and Seating Programmes made it possible to evolve practical approaches to patient needs from a multidisciplinary perspective. Dr. G. Hahn, the medical director of this programme, and Dr. H. Thompson, Chief of Plastic Surgery at the Sick Children's Hospital, provided a strong medical foundation for both the research and service activities. I would also like to thank the contributions of Mrs. H. Healy, Mrs. A. O'Rourke and Mrs. L. Mochan for their devotion to treating and educating our patient population.

My thermography research colleagues at The Ontario Crippled Children's Centre and the Defence and Civil Institute of Environmental Medicine (DCIEM) facilitated the combination of engineering, physics, and physiological principles in interpretation of thermographic observations. Mr. A.F. Filippone, my research associate, provided software and hardware support for the development of our quantitative thermographic system. Dr. L. Reed and his colleagues at DCIEM provided the isotherm areameter for the basic quantifying of the thermographic data and participated in a joint investigation of normal subjects. Through personnal communications Dr. Paul Brand has been a special inspiration through his previous work with thermography and desire to bring practical benefits to his patients with Hansen's Disease.

This research has been possible through the financial support provided by the Variety Club, Tent 28, for the thermographic system and the National Health and Reasearch Development Programme for supporting research grants.

My deepest thanks is to Mary, my wife, for providing emotional and editorial support over the past years and to whom I dedicate this thesis.

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CHAPTER 1: INTRODUCTION

1.0 OUTLINE

The research presented in this dissertation deals with the prevention of pressure sores, particularly with respect to wheelchair sitting and the Spina Bifida population. The aetiology of pressure sores is reviewed for all wheelchair users, and the incidence of Spina Bifida is presented to demonstrate the magnitude of the problem.

The Ontario Crippled Children's Centre (OCCC) initiated a protective seating programme from which was identified the need for the thermography research presented in this thesis. The OCCC tissue trauma programme is briefly reviewed and a specific outline of the research plan described. A summary of the research results follows, with particular reference to the author's contributions.

1.1 PRESSURE SORE PROBLEM

1.1.1 Incidence of Pressure Sores

Most surveys of pressure sore incidence have used data drawn from selected populations in hospitals and other institutions. Those based on a plastic surgeon's review of his caseload refer only to that segment of the patient population for whom surgical intervention was required. Of greater interest are studies designed to determine the scope of this problem for a more general population, providing a statistical basis for impact studies evaluating prophylactic regimens. Such surveys, to be complete, must obtain detailed information describing the location, severity, and frequency of pressure sores.

Pressure sores were found to be prevalent in the spinal cord injured patients just after WWII Poer(1946), Kennedy (1946) and

Kuhn (1947) reported rates as high as 57%-85%. Later, Yeoman and Hardy (1954) studied a civilian population of spinal cord injured patients, and discovered a pressure sore prevalence of 55%.

The pressure sore problem has increased as improvements in primary care have prolonged the lives of the elderly and chronically handicapped persons, Dansereau and Conway (1964) and Schell and Wolcott (1966). Advances in antibiotic therapy and plastic surgery techniques during the past 35 years have made it possible to save many patients who would otherwise have died. Hence, the population at risk for pressure sores continues to grow.

Petersen and Bittman, (1971) conducted a survey of hospitals and nursing homes in the Danish province of Aarhus by means of questionaires. They discovered that the incidence of pressure sores within the hospital system, was in the order of 3%. In a similar study conducted by the University of Strathclyde, Jordan and Clark (1977) found the incidence within the Greater Glasgow Health Area Board to be 8%. In both of these studies a high incidence of ischial and sacral pressure sores amongst those who were wheelchair bound was reported.

It was noted in the Strathclyde study, that an increase in the incidence of pressure sores within the 10-19 year age group, was attributable to the presence of a large surviving population of children with Spina Bifida. Although neurosurgical techniques, such as primary closure of the myelomeningocele and atrio-ventricular shunting of hydrocephalus, have dramatically increased their survival rate, all have some degree of paraplegia.

Of the paraplegic children in the study, 21.6% had pressure sores. In general two risk factors were found to be important:

immobility, and incontinence of urine and/or feces. In addition, those who had multiple sores also had more severe sores. Petersen and Bittman (1971) found similar trends among spinal cord injured patients, thus confirming the risk children and young adults with Spina Bifida have of acquiring pressure sores.

At the Ontario Crippled Children's Centre (OCCC) the prime service mandate is for the care of children, of whom those with Spina Bifida represent the second largest group. For this reason, the particular focus of this research lies with the prevention of pressure sores in the wheelchair bound portion of the population.

1.2 SPINA BIFIDA: THE STUDY POPULATION

1.2.1 The Incidence

In the first half of this century the incidence of Spina Bifida appears to have reached epidemic proportions in the North Eastern United States, Janerich and Piper (1978) and in Northern Ireland and Belfast, Elwood and Nevin (1973). In addition, it has been increasing in Britain over the last one hundred years, Rogers and Weatheral (1976). Epidemiological studies of neural tube disorders in Hospitals in Northern Ireland, the United States and South Africa, have not demonstrated any strong correlation with geographic or environmental factors. The most predominant theory; however, is that there does exist a polygenic susceptibility to some unidentified environmental trigger factors.

It is difficult to predict the future population of children presenting with this deformity. The factors to consider are:

1) the development of screening techniques leading to the early detection of Spina Bifida (i.e., the use of amniocentesis to detect raised levels of alpha-fetoprotein in the amniotic fluid, Brock and Sutcliffe (1972) or the imaging of spinal malformations by ultrasound , Littlefield et al.(1974));

2) the public attitudes towards termination of such pregnancies;

3) the number of infants born to mothers not considered to be at high risk and hence, not subject to screening procedures;

4) prevalent attitudes and law towards postnatal treatment of such children, Lorber (1972) and Heyman and Holtz (1975), who discuss criteria for treatment and the legal implications of refusing unusual care;

5) the detection of environmental trigger factors which can be guarded against (such as ingested toxins from smoking, alcohol and drugs, or from emotional stress); and

6) the improvement in living standards in all socio-economic groups, leading to improved nutrition and general health during pregnancy.

An information service publication produced by the Institute for Research into the Mental and Multiple Handicap (1978) contains a discussion comparing the relative cost to society of early detection and termination of pregnancy, versus the lifetime costs of caring for such individuals (£ 4,000 vs £ 100,000). The combination of present cost escalations and the compromized lifestyle of the child with Spina Bifida suggest that preventative measures will be more fully used in the future. In 1980 there were almost 1000 children with Spina Bifida registered with the Ontario Easter Seal Society, out of a provincial population of 8 million.

1.2.2 The Disability; It's Pathology, Prognosis and Complications

The condition known as Spina Bifida results from a malformation of the spinal cord. Of the several ways in which the condition can manifest, we are concerned with the most severe, the myelomeningocele, which results in a a complete paraplegia below the level of lesion. When the deformity is associated with hydrocephalus, the problem is greater because the child may also have compromised intellectual function.

During the late fifties and early sixties, neurosurgical techniques were developed to control hydrocephalus in the neonatal period by means of the ventricular shunt, permitting the drainage of cerebral spinal fluid. Unfortunately, although this intervention saved lives, there often remained a cognitive handicap which presented formidible hurdles for many of these children as they attempted to find a niche in society. Nevertheless, a large number of children have survived and rehabilitation centres are faced with large numbers of severely multiply handicapped children, with a life expectancy approaching that of the able-bodied.

In response to this challenge special habilitation programmes were developed, Carrol (1976). However, the many interrelated disabilities of the multiply handicapped person can generate a domino effect, bringing their overall activities to a halt. For example, if bladder incontinence is poorly managed, the sitting environment of wet diapers or clothing increases the risk of pressure sore development. Consequently, systematic monitoring of many problem areas is required, until the child is sufficiently responsible to achieve independence. Those children who have adequate intellectual resources may then progress to lead

independent lifestyles. Unfortunately, the majority do not have the skills to achieve this goal resulting in frustrations and uncertain futures, Lorber (1972). This trend has led to a reassessment of the philosophy of radical treatment at birth for hydrocephalus. It would appear that there will be developed, accepted criteria for the selection of patients who will receive such treatment.

1.2.3 Impact of Pressure Sores

In a 10 year longitudinal study of 524 patients with Spina Bifida, a pressure sore prevalency rate of 40-50% was discovered, Okamoto et al. (1983). When pressure sores do occur, they create an extensive disruption in the child's educational, vocational and social activities. This can lead to depression and loss of motivation if the problem becomes recurrent. Subcutaneous pressure sores, if present at an early age, will cause loss of tissues which can never adequately be replaced. Hence a vicious cycle is generated of superficial initial pressure sores increasing the risk of subsequent more serious lesions.

In the Spina Bifida programme developed at OCCC, ambulation is encouraged at an early age in devices such as the parapodium, Carrol (1976). This affords the best opportunity of exploring the environment and of experiencing the upright position. As their weight increases rapidly at puberty, these patients are unable to maintain an adequate power to weight ratio in their upper extremities and suddenly find it necessary to become full time wheelchair sitters. Self-protective habits such as regular weight shifting must then be learned in a very short period of time. During adolescence, the social and educational activities around the child increase and little consideration is given by the individual

to such self care routines. This was reflected in Okamoto's findings of a sharp rise pressure sore prevelence during the adolescent years.

For these reasons, it seemed logical to focus on the development of a tissue trauma programme to prevent pressure sores through the design and provision of prophylactic wheelchair seating.

1.3 APPROACH TO THE PROBLEM OF PRESSURE SORE PREVENTION

1.3.1 Team Approach to Patient Management

It was felt that the development of pressure sores often involved more facets of a person's rehabilitation than seating. Frequently it was found that patients with severe social disruptions at home developed sores, which effectively removed them from a threatening environment. Although there are many technical factors which might contribute to the development of pressure sores, the successful prevention of recurrence depends upon the cooperation of a well informed patient, motivated to remain healthy, once given the tools and information to cope with this ongoing threat. Preparation involves therapy, psycho-social counselling, technical aids and medical input. These protessionals constitute the multidisciplinary team which works with the patient to prevent the development of pressure sores.

1.3.2 Elements of a Tissue Trauma Programme

For maximum effect, a tissue trauma programme must include a number of activities. Multidisciplinary assessments are required to develop an in- depth risk profile for the individual patient. A decision making group, such as a clinic team, must set goals and monitor the progress of the individual patient. Parent and/or guardian education is necessary to transfer concepts and techniques to the patient at risk.

Such a programme requires objective measurements and coordinated information management. The team must be aware of the overall habilitation plan for the patient, to anticipate any major changes in lifestyle which would increase the individual's pressure sore risk.

1.3.3 Role of Rehabilitation Engineering

The engineering tools, which can be helpful in the prevention of pressure sores, relate to the measurement of risk and the design of support surfaces. These two activities should be interrelated, so that the selection of a seating system for the individual patient can be provided on a systematic basis. There are many choices of materials and design concepts for seating; however, there is a need to "problem" solve on an individual basis prior to prescribing a seat. This problem solving may include periods of trial sitting during which measurements may be used to determine the best wheelchair seating system.

1.4 RESEARCH OBJECTIVES

1.4.1 Seating Process

There are four steps which describe the decision making process in selecting a seating system: 1) patient assessment; 2) goal setting; 3) seat fabrication and measurement; and 4) evaluation. If an individual physician simply prescribes a seating cushion as a result of a physical examination and history; valuable biomechanical and tissue pathology data may not be used.

Commercial cushions can be expected to suit a spectrum of patients. However, guidelines for identifying this group are never provided. A seating programme can incorporate many facets of this

selection process and also provide for individual needs through custom made devices. Objective evaluation of trial seats has not been possible so that patients are faced with unknown risks after a change in seating. This report deals with the use of thermography as such an evaluation tool.

1.4.2 Seating Evaluation: The Need

Evaluative measures must describe the potential for success or failure of a given support surface to prevent pressure sores. Measurements of the forces and other physical conditions at the interface of the patient-seat interface describe the loading conditions for the weight supporting tissues but not their viability. Direct measurement of tissue reactions to loading, as a result of sitting, is required to meet this objective. The ultimate evaluation will, of course, be the prevention of pressure sores in a study population within a classified patient group; however, the time response is too slow for the purposes of seating design and development. For these reasons, a rapid method of seating evaluation, through the monitoring of tissue response to pressure would be a critical element in the development of a research tissue trauma seating programme.

1.4.3 Assessment of Thermography for Seating Evaluation

Thermography had been used by Dr. P. Brand (1971) to monitor patients with insensitive feet who were in the process of receiving protective footwear. The research conducted in Carville, Louisiana, indicated that the subjective assessment of thermal patterns provided a reliable prediction of the success or failure of custom shoes in preventing recurrent pressure sores. While the loading

conditions on buttock tissues produced by wheelchair sitting are considerably different from those of the footwear studies, the concepts of this thermographic application were considered similar.

This research programme set out to determine whether or not thermography could be used clinically as a guide to seating selection, and whether or not its specificity could be improved with objective and quantitative techniques.

1.5 RESEARCH PLAN

1.5.1 Technical Development of the Thermographic System

The research programme began with the acquisition of a basic black and white AGA 680 medical thermograph and a colour monitor to enhance thermal patterns and gradients. This report stresses not the development of hardware, but the build up of a complete data acquisition and analysis system. The initial studies were conducted with the basic thermographic system and still colour thermographs. An isotherm areameter was obtained through cooperative studies with the Defence and Civil Institute of Environmental Medicine (DCIEM). This permitted the automatic sampling of isotherm areas within a data window which was adjustable in size and location on the colour video monitor. A time-lapse cine recording system was used to continuously record the thermograph imagery to enhance the perception of time based changes in the thermal patterns. The combination of these two systems, along with the still photographic records, permitted the documentation of the thermal responses of tissues after sitting.

1.5.2 Determination of the Minimum Conditions for Quantitative Thermographic Techniques

The development of the automatic areameter at DCIEM (Department of Defense report 3647C-01, see Appendix V), presented the challenge of determining those conditions, under which reliable quantitative thermographic data could be obtained. This portion of the research was conducted in conjunction with DCIEM, in their environmental "Tropical" chamber. Experiments were designed to ascertain the sensitivity of the quantitative data to induced hyperaemia and the influence of environmental parameters, such as ambient temperature and relative humidity, in characterizing this reaction. Able-bodied subjects were used with experimental seats designed to produce extreme ranges of sitting pressures.

1.5.3 Patient Studies

Preliminary studies were conducted to test the set-up of the quantitative system at OCCC. This involved applying the quantitative techniques to patients who were recieving a regular review, or who were undergoing intensive studies during seating evaluation. The protocol and data retrieval techniques were modified to suit the clinical limitations of positioning patients and locating local areas of tissue at risk.

1.5.4 Analysis of Results

In Chapter 4 quantitative data obtained from thermographs were compared with the qualitative tissue quality measures graded from colour skin photographs. Typical peak and relative temperature

ranges were observed and compared by calculations of averages and standard deviations of selected groupings.

Chapter 5 presents the results of subject trials at DCIEM and the analysis of peak temperature measurements and areameter data. The development of the "accumulated area graph" is highlighted as the initial display, which reflected the changes in experimental conditions most dramatically and the average temperature plots which compressed the areameter data to a single time dependent locus.

The results of the initial trials with patients using the protocol developed in the environmental studies, with changes introduced to accommodate the particular data acquisition system developed at OCCC, are described in Chapter 6. The areameter data were normalized with a second order exponential model to further characterise the cooling process.

Chapter 7 summarizes the findings of these three aspects of the thermographic reseach, and also outlines the findings of the analysis of patient data. It is the combination of these measurement techniques which form the basis for the seating programme and their integration into the seating process, which highlights the clinical contribution of this research.

1.6 A SUMMARY OF RESULTS

1.6.1 Developed Thermographic System

A unique combination of measurement tools is presented in this report with emphasis on the thermographic system. A novel data recording system was developed with microfiche film as a medium to facilitate storage to facilitate storage and retrieval of still thermographs. Time-lapse photography was used to qualitatively

study time dependent changes in thermal patterns and quantitative analysis was possible through the use of a computer controlled areameter.

1.6.2 Results of Able-Bodied Subject Trials

The tests at DCIEM demonstrated the sensitivity of the quantitative data to changes in ambient temperature, greater than ± 0.5C°. The measurements were less sensitive to changes in relative humidity as step changes of +10% did not produce fluctuations in measured skin temperature. In this respect, the relative humidity changes observed in the hospital environment were unlikely to introduce quantitative errors. Draughts at both DCIEM and OCCC were kept down to levels not measureable with an anamometer.

1.6.3 Results of the Patient Trials

Specific observations, useful in the interpretation of thermographic data obtained from seating trials, have been recorded. There are definite indications of tissue inflammation, either before or after the tissue has been loaded. Prolonged hyperthermic responses were interpreted as the response of damaged tissue to ischaemic loading conditions. This was based upon the research findings of Brand (1971) and the association of this reaction with tissue sites which exhibited visible symptoms of inflammation. Patients studies are reported in both Chapters 4 and 6. This summary combines some of the main findings described.

Temperature ranges were recognized as relating to the decisions used in the clincal seating programme. Comparisons of tissue quality, as defined by clinical observations, and maximum skin

temperatures after 15 minutes of ambient cooling, were used to develop guidelines for clinical thermography. It is stressed that these guidelines reflected the practice at OCCC, not experimental physiological data.

It was felt that automated measurement techniques would be more reliable, and could capture time based changes in skin temperature under cooling conditions. Peak temperature responses were identified for normal subjects after exposure to high levels of pressure over the ischial tuberosities. In addition, mean imaged temperatures provided were sampled and compared to describe the cooling characteristics of skin after loading.

It was determined from the normal subject trials that the area of tissue response was sufficiently small that the camera had to be used at minimum range to provide adequate resolution. In addition, the high risk weight-bearing sites, adjacent to the perineum, were difficult to monitor as any slight subject movement introduced considerable noise into the desired signal.

The mean imaged temperature curves were further described by a quadratic semilog, or power fit. The coefficients were calculated for groupings of data to detect sensitivity to test conditions; however, there was insufficient strength in any such trends to be defined with the available data. The scatter plot of these coefficients against each other suggests a first order fit may be adequate for this type of analysis. Further tests would be required to refine the limits of confidence of such models and the interdependence of coefficient values and graded tissue pathology.

1.6.4 Author's Contributions

The author has played a major role in the development of the Tissue Trauma Programme at OCCC. These activities included:

1) The accumulation and organization of a broad range of literature for inclusion in the educational programmes.

2) The development of systematic protocols to integrate measurement techniques into the seating process, such as a glass table with edge lighting, pneumatic pressure transducers, seat timer systems, and thermography.

3) Guidelines were identified which reflected the use of thermography in the OCCC clinical practice.

4) Thermography was used as an evaluative tool, based initially on the approach reported by Dr. Brand (1971) in connection with his footwear clinic. Further quantitative techniques were introduced and tested in an environmental chamber at DCIEM, to determine the minimum conditions for such studies. It was estimated that ambient temperature should not fluctuate more than 0.5C° during an examination.

5) A post-sitting skin temperature of 34.5°C was used as a conservative warning temperature after 15 minutes of cooling. The general concept developed during this phase of the research was that much of the relevant thermographic data was to be found in describing how the skin cooled over a period of time after a load had been applied. This was studied by modelling the change in average temperature.

6) A quadratic function was fitted to the semi-log plot of the average temperature vs. time. Further basic research would be required to define the quantitative aspects of tissue response to pressure and improvements in the thermographic recording and analysis offline would improve the specificity of the data sampled.

CHAPTER 2 BACKGROUND TO THE PROBLEM

2.0 INTRODUCTION

This chapter presents a detailed review of the literature dealing with the causes and prevention of pressure sores. The background discussion then shifts to describe those clinical programmes which have evolved to deal with the problems of specific groups of patients.

The section discussing the cause of pressure sores begins with a description of both cellular and macroscopic pathophysiology. Extrinsic and intrinsic factors, thought to contribute to the development of pressure sores, are then presented to demonstrate the potential hazards of support surfaces.

The current approaches to the design of support surfaces are reviewed in detail, showing the variety of theories and devices recently developed and emphasizing the significance of the divergence of opinion on prophylactic seating. This reinforces the concept that no one system is best for all wheelchair users and emphasizes the need for objective evaluation techniques.

A number of pressure sore prevention programmes are contrasted with respect to philosophy, regimen and apparatae . The tissue trauma programme which evolved at the OCCC is described, including the proposed clinical use of thermography.

2.1 CAUSE OF PRESSURE SORES

2.1.1 Patho-physiology of Pressure Sores

Cameron (1967), in his textbook of pathology, presents the following categories of pathogenic agents: ischaemic, physical traumatic, chemical, microbiological, immune response, and

genetic. Most authors agree that the primary cause of pressure sores is pressure induced ischaemia: The corresponding process of cellular destruction is called coagulation necrosis described by Antypas (1980).

The process of tissue deterioration is a continuum, and hence the definition of various states of tissue health must be empirical, leading to discrepancies in terminology when grading the severity of pressure sores. The stages are described in Table 2.1, based upon observable microscopic and macroscopic changes, and graphically portrayed in Figure 2.1. However, with new technology, it may be possible to obtain more objective pressure sore assessments through the use of computer aided tomography, Firoozna (1982) or by soft tissue imaging with nucular magnetic resonance.

Many of these tissue changes were initially studied with experimentally produced pressure sores in animals. These authors sought to determine critical combinations of intensity and duration of pressure which would lead to irreversible cellular damage. More recently, it has been recognized that the process of tissue deterioration can also be generated by many repetitions of pressure/duration conditions, which, applied only once, would not induce observable pathological changes. It is this latter process, described in detail by Brand (1971), which represents the problem faced by any full time wheelchair user.

2.1.2 Intrinsic Factors Contributing to Pressure Sores

The initial clinical assessment of the patient subject to pressure sores, should determine those intrinsic characteristics which place one at risk. However, there has been no common agreement on the methodology of preparing a risk factor profile for

FIGURE 2.1 PATHOPHYSIOLOGY OF PRESSURE SORES

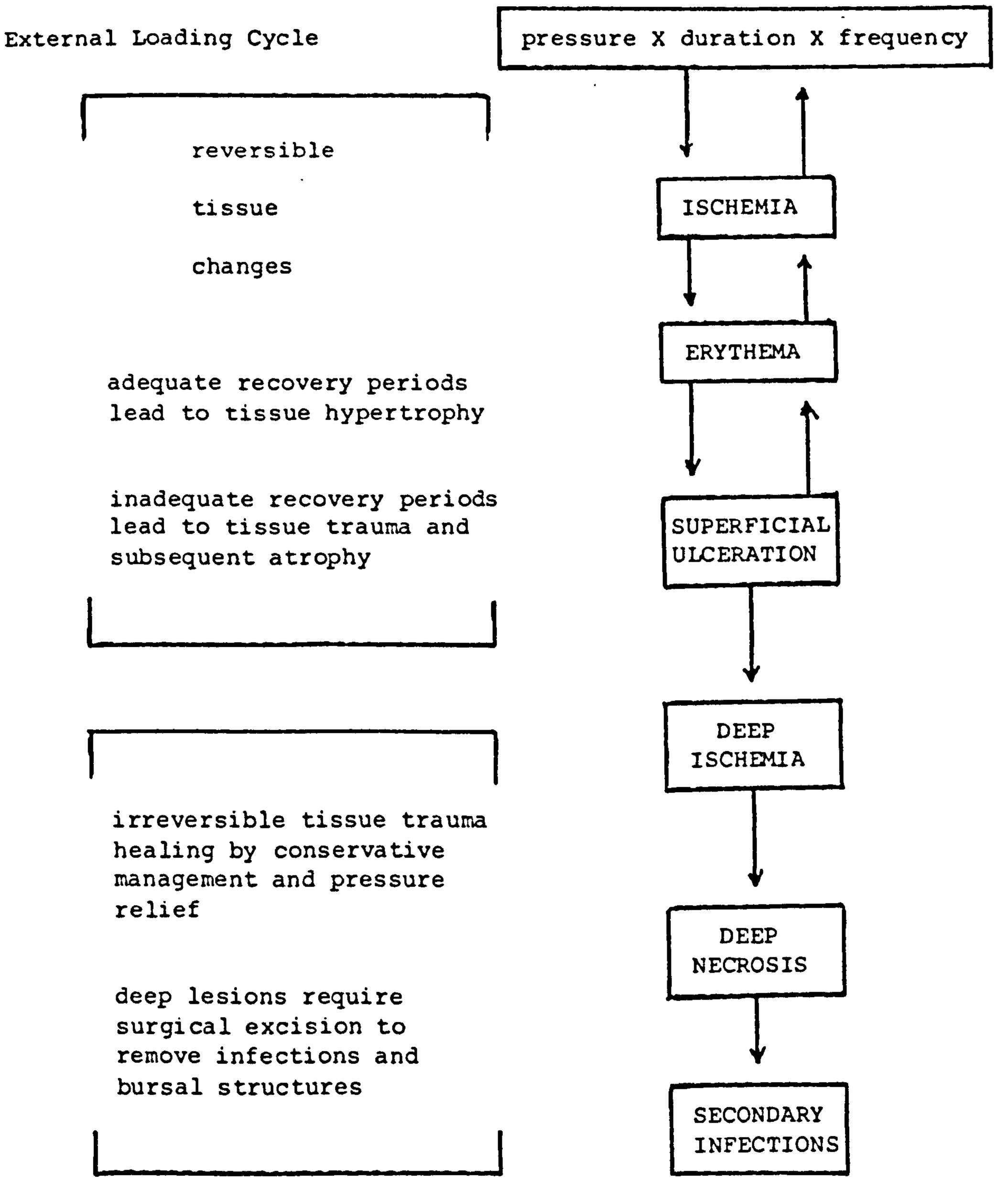


TABLE 2.1 PATHOPHYSIOLOGY OF PRESSURE SORES

TISSUE STATE	MACROSCOPIC CHANGES	MICROSCOPIC CHANGES
STAGE I "Hyperaemia" Ischaemia induced for short periods of time (eg. 30 minutes to one hour) will produce reversible changes in the tissues.	The skin will appear red upon release of pressure but this will disappear within 1hr.	Cells will show infiltration and cloudy swelling. The hyperaemic response is thought to be triggered by a build up of metabolites
STAGE II "Ischaemia" Reversible tissue changes result after 2-6 hours of ischaemia	Skin redness will disappear within 36 hours of pressure relief. This redness will blanche when pressure is applied.	Fatty changes are seen in the cells along with hyaline conjunctive changes. Interstitial capillary hemorrages and extravasation of the cells will be observed.
STAGE III "Necrosis" Ischaemia maintained for 6 to 15 hours will begin a process called coagulation necrosis.	The skin will be discoloured with a dusky blue appearance which will not blanche when pressure is applied. This may be followed the development of a hard subcutaneous lump.	There is evidence of frank hemorrage and karyolysis. In addition proliferation of polymorphonuclear leucocytes will be evident.
STAGE IV "Ulceration" Ischaemia maintained for more than 15 hours will produce frank ulceration as evidenced by an open lesion. This may heal over a long period of time or may require surgical repair.	This wound will be open with infection producing some exudate. It may be a shallow lesion or a deep bursa in the underlying tissues.	There will be destruction of subcutaneous tissues with evidence of fused cell structures, enzyme dissolution and phagcytic exudate. The damage may extend as far as the bony structures leading to periostitis and osteomyelitis.

tissue trauma patients. For the purposes of discussion, the author has empirically created such a profile based upon clinical experience and factors described in the literature.

Four categories were chosen for those parameters considered intrinsic to the individual: anatomical, neurological, medical and psychological. Although mobility has been described as a risk factor, Norton (1962), Peterson (1971) and Barbenel (1977) it is considered in this study to be a function of the other parameters.

Each parameter in Table 2.2 is discussed in relation to its possible influence on:

(F) Loading frequency - the number of occasions within a given period of sitting that susceptible tissue sites are loaded;

(D) loading duration - the length of time for which the load is applied on each occasion;

(M) magnitude of loading - the peak forces or stresses applied to the weightbearing tissues including both normal and shear stresses; and

(R) tissue resistance - the capability of tissue sites to recover from comparable ischaemic insult.

The interrelationship of these factors is best demonstrated by citing a case study (a list of patients, designated by initials, is presented in Appendix I). Patient (CD-1) had a dormant bursa over his left ischial tuberosity. Shortly after returning to school this became acutely inflamed and required hospitalization. His sitting habits had changed abruptly to accommodate the school schedule: He sat for longer periods of time, (D-increased); more often, (F-increased); and on the same wheelchair cushion, (M-constant). Within a short period of time he developed a low grade inflammation,

TABLE 2.2 INTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

Categories	Parameters	(F)	(D)	(M)	(R)
ANATOMICAL	ORTHOPAEDIC DEFORMITIES		X	X	
	SOFT TISSUE STRUCTURES		X	X	
	TISSUE QUALITY (HEALTH)				X
NEUROLOGICAL	SENSORY LOSS		X	X	?
	SPASTICITY		X	X	
	ORGAN FUNCTION LOSS				X
MEDICAL	NUTRITION (DEFICIENCIES)				X
	DISEASE PROCESSES	X	X		
	INFECTION (LOCAL/SYSTEMIC)				X
PSYCHOLOGICAL	COGNITIVE SKILLS	X	X		
	EDUCATION	X	X		
	BEHAVIOURAL	X	X		

NOTE: This chart lists factors which the author believes increase the pressure sore risk. The coding emphasizes the way each parameter may act to the detriment of the patient. Specific implications must be related to an individual patient through careful assessment with the use of objective measures where possible.

CODES: "X" represents areas in which the author considers the parameter to have an influence and "?", areas of continued debate in the literature. (F)≡ Loading Frequency; (D)≡ Loading Duration; (M)≡ Loading Magnitude; and R ≡ Tissue Resistance.

EXAMPLES: Typical patient situations which illustrate these relationships are presented in Appendix I.

and his resistance to the new sitting stresses decreased (R-decreased). This example demonstrates how physical parameters may be used to describe changes in pressure sore risk.

The reviews presented by Kosiak (1959), Schell and Wolcott (1966), Merlino (1969), Berecek (1975) and Vasconez et al.(1977) described risk factors such as nutritional status, anemia, infection, incontinence, tissue oedema, spasticity, mental condition and mobility. The following examples expand on the significance of the groups of risk factors presented in Table 2.2.

Anatomical:

Structural changes of the musculo-skeletal system, connective tissue, or skin may increase the pressure duration and magnitude, and decrease tissue resistance to ischaemia. Without an ongoing physiotherapy program, hip and knee contractures may develop in any full time sitter. In addition, spinal deformities may lead to asymmetrical weightbearing and reduced functional mobility. These secondary complications of paraplegia are particularly severe for children with Spina Bifida because the immature spine is susceptible to the development of severe compound curves during growth.

There is much debate as to which tissues are most suitable for supporting body weight. Keane (1979) discusses the minimum support requirements for humans, and argues that soft tissues which contain muscle and nerves are highly susceptible to ischaemia. In support of this argument he observes that these tissues slide away from bony prominences during weightbearing.

In disagreement with this theory, Schell and Wolcott (1966) noted that patients with soft tissue atrophy, caused by motor

paralysis, had a higher risk of developing pressure sores than heavier patients with more subcutaneous tissues for pressure distribution .

For the purposes of this study, the quality of the weight supporting tissues, has been described with respect to clinically observable irreversible changes (tissue type), and transient changes in response to acute ischaemic insult (tissue condition). Both of these types of changes may influence the same risk parameter. Internal tension is intensified under load because of the structural rigidity induced by the permanent change in tissue elasticity as a result of scarring. Oedema, secondary to inflammation, will increase intracellular fluid content, temporarily reducing the elasticity of the tissue, and thereby also intensifying internal pressure under external loading conditions.

Neurological:

A "neurotrophic factor" has been thought significant in reducing the resistance of insensitive skin to ischaemia. This theory, originally proposed by Charcot (1879), hypothesized that denervation of tissue disturbed its nutritional supply. Munro (1940), extended this hypothesis by proposing a disturbance in the autonomic reflex arc controling local circulation. Holloway, Allen et al. (1976) observed no differences in autoregulated blood flow after pressure release when comparing paraplegics and control subjects. Lee and Bennett (1981) studied pressure, shear and blood flow in the vicinity of the ischial tuberosities of 15 paraplegic subjects during sitting. Both pressure and shear values for the paraplegics were greater than those for normal control subjects, while the corresponding blood volume flow rates were much smaller.

They hypothesize from these findings that loading conditions are more severe in addition to the presence of a neurotrophic factor.

When local skin and muscle tissue innervation is replaced by the surgical use of neurovascular flaps the pressure sore cycle is usually stopped, Krupp et al. (1983). In addition to this observation many, patients with neuromuscular diseases, who have the same mobility constraints as a quadraplegic, but intact skin sensation, remain pressure sore free for extended periods of time. Although the neurotrophic factor may remain unresolved, insensitive skin appears to represent a high risk for pressure sores.

Spasticity is often cited as a contributing factor althougn there have been no formal studies to assess this parameter. Nevertheless, posture and balance will suffer, particularly in the presence of spasticity of the hamstring musculature, imposing additional shear stress on the weightbearing tissues. On the other hand, it should be noted that there may be positive aspects, such as increased blood circulation induced by the muscular activity characteristic of spasticity.

Functional loss of organs resulting from paresis may place the subject at an increased risk. Of particular note is the fact that virtually all complete spinal cord injuries result in patients aquiring a neurogenic bowel and bladder. Poor management of incontinence will lead to additional risks arising from maceration of tissue exposed to pressure, friction and moisture, Barton (1976), Goldstone and Goldstone (1982), and Ek and Bowman (1982).

Medical:

Typical parameters are those based on systemic changes induced by nutritional imbalances and disease processes. Freeman (1919), McCormick (1941), Homans (1940), Mulholland et al.(1943), and Vasile and Chattin (1972) have reported that protein deficiencies, avitaminosis and low haemoglobin levels, predispose a patient to tissue breakdown. These studies refer to the geriatric patient who often presents in an emaciated condition. It should be stressed however, that the young paralyzed person may be equally susceptible to these conditions as a result of neglect, recurrent infections, nephron loss and, amyloidosis.

Psychological:

In the author's view psychological and physical risk factors operate on each other. The patient's physical abilities describe the tools he has to work with; and his psychological health and motivation determine how he will use these. Guttman (1976) has long recognized the significance of patient cooperation and participation in the prevention of pressure sores. The interrelationship between rehabilitation duration and outcome with scores on the MMPI-168, SCL-90 and PECS psychological tests was conducted by Malec and Neimeyer (1983). They found agreement between the tests on measures of distress and depression and that high scores in these aspects were associated with longer rehabilitation periods.

Psychological parameters are difficult to measure objectively and are subject to constant change induced by the patient's continuing life experience. "Behavioural Engineering" describes the study and modification of such parameters with biofeedback

techniques and lift warning monitors are an initial application of this technology for the prevention of pressure sores.

The complex interrelationship of all of these intrinsic risk factors within any one individual demonstrates the importance of conducting careful individual assessments. The weighting of these factors for identified patient groups has yet to be determined in any formal way. For this reason, clinical studies must take pains to describe target patient groups

2.1.3 Extrinsic Factors Contributing to Pressure Sores

The external tissue risks can also be viewed in terms of their influence on the frequency (F), duration (D), and magnitude (M) of the applied loading as well as the resistance (R) of the tissues to ischaemic insult.

These factors were classified into three groups; namely a) interface forces, b) interface environmental parameters, and c) lifestyle parameters, see Table 2.3 "Extrinsic Factors Contributing to Pressure Sores". Categories (a and b) describe the physical conditions at the skin surface, of which some can be measured by appropriate transducers. Lifestyle parameters are determined by the physical demands inherent in the individual's personal activities and the physical care the handicapped person experiences.

TABLE 2.3 EXTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

Categories	Parameters	Loading Conditions (F)	(D)	(M)	Tissue State (R)
INTERFACE FORCES	NORMAL			X	
	SHEAR (STATIC)			X	
	SHEAR (DYNAMIC)			X	
INTERFACE ENVIRONMENT	TEMPERATURE				X
	VAPOUR PRESSURE				X
	CHEMICAL				X
LIFESTYLE	ACTIVITIES	X	X	X	
	REGIMEN (PERSONAL)	X	X		X
	REGIMEN (IMPOSED)	X	X		X

NOTE: This chart lists those extrinsic factors the author believes to be essential in describing the risks imposed on the individual patient by a particular support surface and lifestyle. Since there is an interrelationship between intrinsic and extrinsic factors, this table either directly or indirectly includes factors described in the literature.

CODE: "X" denotes the presence of an association between the listed extrinsic factors and a resultant impact upon the loading conditions or tissue resistance to ischaemic insult.
(F) ≡ Loading Factors Frequency; (D) ≡ Loading Factors Duration; (M) ≡ Loading Factors Magnitude; (R) ≡ Tissue Resistance

EXAMPLES: Typical patient situations which illustrate these relationships are presented in Appendix I.

Interface forces:

The external forces may be described in the following categories:

		APPLICATION	
		STATIC	DYNAMIC
EXTERNAL LOADING CONDITIONS	NORMAL	pressure	pressure
	IN-PLANE	shear	friction

Two aspects of the surface loading forces must be considered: 1) the complex pattern of forces and stresses arising when weight-bearing takes place and, 2) the physiological response.

Bennett has published a series of theoretical models describing the mechanics of transferring load to flesh in the Bulletin of Prosthetic Research, Bennett (1971a, 1971b, 1971c, 1972, 1973, 1975 and 1979). These modelling techniques are suitable for simulating basic design concepts of seating biomechanics. It is not, unfortunately, a suitable technique for evaluating the risks of a particular patient, as there are too many variables to allow for modelling of internal stress state in the tissues. These theoretical studies indicate that the design of the support surface plays an important role in determining local loading conditions. For this reason, it is important to emphasize that research and evaluation of these devices are worthwhile.

Static and dynamic shear forces are described as separate mechanical risk factors, (see Table 2.3). If a patient's posture tends to push him/her forward in the chair, frictional stresses will contribute to the occlusion of local blood supply, Reichel (1958), Bennett (1972 & 1979) and Lee and Bennett (1981). This type of risk may be reduced by the use of postural supports to balance a sweeping lumbar kyphosis. In addition, the friction, developing in a sliding contact, may lead to abrasion and thereby reducing the resistance of tissues to further loading, Dinsdale (1974).

Interface Environment:

Daniel et al.(1978), in his review of the literature has included incontinence and humidity as parameters of extrinsic risk, and Kosiak et al. (1958), with a similar list, include skin temperature. Cochrane and Palmieri (1980) have reported on tests to evaluate seating systems by combining laboratory and interface tests. The latter included pressure, humidity and temperature measures of skin environment.

If moisture is continuously being absorbed by the skin, maceration can take place, particularly in the presence of shear forces. Clinically, the typical site of onset lies in the intertrigenous zone between the buttocks, and immediately over the coccyx. When such incontinent patients have a lumbar kyphosis, induced by tight hamstring muscles, the resultant shear forces over the coccyx may lead to severe pressure sores.

Fisher et al.(1978) reported in his review that Ruch and Patton (1965) determined the following relationship between tissue, metabolism and temperature. It was estimated that there was approximately a 10% increase in metabolic rate per 1C° rise in

temperature. Several authors have extrapolated from these data, assuming that it is a linear relationship which holds true for all types of tissues under ischaemic conditions. The conclusion then drawn, is that a 5C° relative increase in skin temperature represents a 50% increase in tissue susceptibility to comparable ischaemic levels. If this were true, cooler seats would have an advantage over warm, or insulating types.

Sitting temperatures have been reported for various types of cushions by Brattgard et al.(1975), Fisher et al.(1978) Stewart et al.(1980) and Cochrane et al. (1981). Patterson and Fisher (1980) conducted day long studies sampling measures of interface pressure, pressure relief and skin temperature. Large pressure variations were found, partially due to the errors associated with pneumatic transducers, and the skin temperature was found to have a rise time of approximately 2 hours. This was the first attempt to define a set of conditions throughout a sitting day. However, it is not possible to relate the results of such physical data directly with metabolic changes in the tissues.

Not surprisingly, specific chemical risks have not been reported. Perhaps this is because of the difficulties inherent in generalising upon such sensitivities. More often than not, the material in direct contact with the patient's skin will be clothing or diapers. The latter, as a form of urine collection, exposes the patient to the ravages of both chronic moisture and ammoniacal scalding. These factors may combine to reduce the skin's resistance to surface infection and breakdown.

Lifestyle:

Lifestyle factors are mentioned as a category of external risks including, as they do, elements of self care and physical activity. Again there are no available data considering such questions as the risk of various wheelchair sporting activities. Should an athlete use the same cushion for basketball and for school? The loading conditions imposed by these two activities are at great variance, the latter being a sedentary activity, and the former, involving violent movements with shock loading.

Seating design can have a great influence on the extrinsic physical risks to the individual patient. In addition, education and training to modify sitting behaviour may improve the loading conditions. For example, pressure reduction may be achieved by provision of an alternative sitting surface for activities out of the wheelchair, or by avoidance of traumatizing activities. Regimens of self care should include self-imposed limits to the duration of continuous sitting, as well as the development of other self-protective behaviours.

2.2 PREVENTION OF PRESSURE SORES

2.2.1 Concepts of Tissue Tolerance

This section reviews the basic research which has contributed to the current understanding of tissue tolerance, ie. the relationship between external loading and subsequent tissue viability. While some researchers have tried to establish a relationship between pressure and time with respect to the development of tissue pathology, others have focused on the identification of critical pressures which occlude blood flow.

General aspects of the pressure sore problem have been reviewed by a number of authors, (Brooks and Duncan (1940), Kosiak (1959), Fernie (1973), Berecek (1975), Kenedi et al.(1975), Vasconez (1977), and Daniels (1978)). This review specifically highlights those findings which pertain to the risks associated with wheelchair sitting and contribute to the science of seating design and evaluation.

The significant findings which have defined thresholds of tissue tolerance to applied ischaemia have been displayed in one graph, see Figure 2.2. The earliest studies attempted to determine the critical time period required for continuous pressure to produce ischaemic necrosis. Ischaemic conditions were imposed through tourniquets on rabbits legs, Heidelberg (1878); on dogs legs, by circumferential external pressure on rats tails, Williams (1938), Brooks and Duncan (1940) and Husain (1953); and on the forearm of a man, Burton and Yamada (1951). Later experiments controlled external pressure over localized sites by mechanical probes, on dogs, Kosiak (1959); and on humans, Rogers and Reswick (1974). Most recently Daniel et al. (1981) have developed a model using direct pressure to the greater trochanter of both normal and paraplegic swine. Caution must be exercised when extrapolating from such a variety of experimental conditions to clinical problems.

The early experiments producing complete ischaemia by means of a tourniquet, were entered on a pressure vs time graph as the equivalent of a sustained high local pressure. Under these conditions, frank necrosis was observed after 12 to 18 hours of complete ischaemia, while Kosiak et al.(1958) established lower limits at 6 hours, in approximate agreement with Husain (1953). This is represented on the tissue trauma graph by a locus of points

TISSUE TOLERANCE

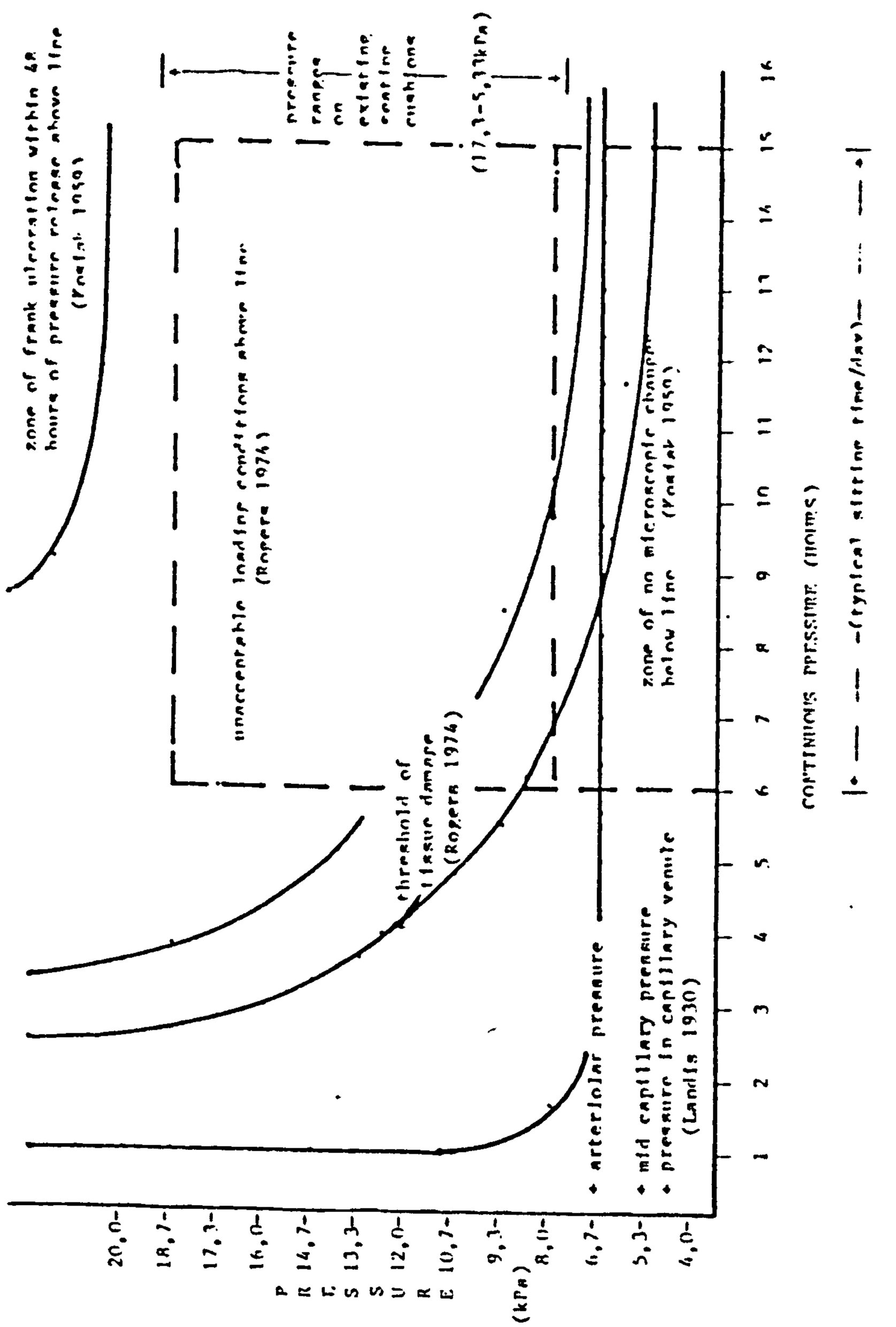


Figure 2.2

at which continuous pressure produces ulceration. The scales in Figure 2.2 display time and pressure conditions commonly found in wheelchair seating. For example, Williams et al.(1938), discovered that continuous pressure of at least 10,7 kPa (80 mmHg) for 48 hours will produce pressure sores. While this type of guideline is useful in the prevention of bed ulcers, it does not accommodate the intermittent loading at higher pressures sustained by wheelchair sitters.

The pressure time curve for the production of ulceration which was developed by Kosiak (1961), also falls predominantly outside this time range, chosen with a maximum of 16 hours continuous sitting. However a pressure-time threshold at which microscopic damage has been observed was 1 hour at 8,00 kPa (60 mmHg). Rogers and Reswick (1974) developed a similar inverse relationship between pressure and time for clinical applications with more leeway then that defined by the findings of Kosiak (1961) and Husain (1953) for microscopic changes. The latter threshold of damage indicates that most of the typical combinations of sitting times and peak pressures fell within a danger zone. The pressure range was assumed to lie between 16,0 kPa (120mmHg) and 4,67 kPa (35mmHg), Lindan (1965). In Daniel's experiments, a much higher set of pressure-duration thresholds were discovered:

i) muscle damage 66,5 kPa (500 mmhg), 4 hours

ii) skin destruction 106,4 kPa (800 mmHg), 8 hours

Landis (1933), used micro-injection techniques to study capillary pressures determining, the minimum pressure threshold at which bloodflow is occluded (the no load conditions). A range of closing pressures was found in the capillary beds; venous pressures at 1,60 kPa (12mmHg), mid-capillary 2,67 kPa (20mmHg), and

arteriolar 4,27 kPa (32mmHg). Burton and Yamada (1951), in their studies of the forearm of a man, used a plethysmograph to determine a relationship between critical closing pressures for the venous outflow of the capillary beds and the surrounding tissues. The early findings of Daly et al.(1975) also indicated that external pressure may gradually cut off blood flow, with a large change occurring at pressures of 2,00 kPa (15mmHg), followed by more gradual decrease up to 12,0 kPa (90mmHg).

Since the "Tissue Tolerance", Pressure versus Time graph is based on continuous pressure application, it provides a useful design guideline, representing a "worst case" loading condition. Unfortunately variations in patient tissue quality cannot be accounted for by the available experimental data. In the application of these guidelines to clinical practice, it can be used as a general guideline for cushion selection and modification.

2.2.2 Regimens of Tissue Care

Complete regimens for the prevention of pressure sores should include such elements as skin care education, tissue risk identification and provision of protective seating. Several authors have described such Tissue Trauma programmes, Edberg et al.(1973), Kavachak-Keyes(1977), Hahn and Black (1977), and Kosiak (1980).

However, patient and staff education represents the mainstay of pressure sore prevention in any programme. Guttman (1975) and Roaf (1975) stressed the development of "pressure sore awareness", a combination of patient education coupled with an acceptance of personal responsibility for implementing appropriate routines. This goal can be a frustrating challenge when dealing with poorly motivated patients.

Many educational packages reflect the findings of Kosiak (1981) and Husain (1953) in recommending pressure relief every one to two hours for the bedfast patient. Comparable advice for wheelchair users varies widely, ranging from regular relief every few minutes, Kosiak (1980) and Keane (1978), to 10-15 minute intervals, Edberg (1973) and Kavacnak-Keyes (1977). Fisher and Patterson (1983) studied the lifting patterns of tetraplegics and found that despite careful training during rehabilitation they lifted well below the recommeded frequencies.

Training and education related to the intrinsic and extrinsic risk factors can be used to modify an individual's techniques of self-care and hygiene. Avoidance of traumatic events, such as poor transfers, and choice of appropriate support surfaces will also serve to reduce the peak pressures over high risk sites.

Risk identification is clinically based on changes in the appearance and feel of the skin. This type of guideline is helpful in the detection of incipient pressure sores, but there is no discussion in the literature of techniques for tracing the probable cause of such trauma. Local textural variations in underlying tissues and the location of the skin pathology with respect to the nearest weight-bearing bony prominence are both relevant clues in detecting the source of trauma being sustained by a patient in his/her day-to-day activities.

A tissue training hypothesis has been proposed by Brand (1975) suggesting that intermittant loading of inflamed tissues, with adequate periods of recovery, will lead to tissue hypertrophy. However, there are no guidelines available for advising patients with respect to their optimum sitting recovery regimen. The concept of tissue training is commonly practiced following pressure sore

surgery, but these regimens vary widely. Improved monitoring of tissue viability may make this approach more consistent.

A systematic approach is required to recommend protective seating. Since there are few specialized seating clinics associated with rehabilitation units many physicians will prescribe cushions, using, as their criteria, results of pressure studies which label types of cusnions as "good" or "bad". This practice discourages the selection of equipment on the basis of the individual's physical and functional requirements.

2.3 PRINCIPLES OF SUPPORT SURFACE DESIGN

2.3.1 Concepts and Classification of Seating Systems

The biomechanical principles of seat design and pressure relief warning systems are presented in this section . These topics are pertinent to the argument presented here: seating is a complex process and its evaluation requires more than patient/seat interface measurements of mechanical forces.

Wheelchair cushions, designed with the objective of preventing pressure sores, must provide control of pressure gradients or reaction forces exerted on the user. This primarily demands the reduction of pressure gradients and shear forces to protect areas of identified risk.

The author's classification of seating systems is based on the materials and biomechanical properties of the devices, see Table 2.4. The material chosen for each system is that of the primary support medium. The biomechanical properties are divided into two large groups; passive or active support. These in turn are subdivided into two further groups; pressure distributing and pressure redistributing. Further descriptors are used based on construction techniques and materials.

TABLE 2.4 CLASSIFICATION OF SEATING SYSTEMS

*MATERIALS	PASSIVE PRESSURE DISTRIBUTING	PASSIVE PRESSURE REDISTRIBUTING	ACTIVE PRESSURE DISTRIBUTING	ACTIVE PRESSURE REDISTRIBUTING
FOAM, ELASTIC	polyurethane	Contoured, Rogers(1974) Ferguson-Pell		Keane(1978) reciprocating seat
FOAM, VISCOELASTIC	terper foam			
FOAM, COMPOSITE	laminated			Warloch(1977) moving wave
PLASTIC	Mechanical Linkages, Ziedman(1978			
METAL				Kosiak(1977) roller seat
GAS (AIR)	Roho			
LIQUID	Mobiloil, Weinstein (1966)			
LIQUID + FOAM	Hydro-Float			
GEL	Magnesium Silicate +.. Bowker(1979)			
PARTICLE	Fluidized-Beads, Lyddy(1978)			

COMMENT: This table presents a classification of seating systems based on their materials, structure and mechanical properties. The mechanical classification into pressure distributing or redistributing is based on the manufacturer's claim. However, although a water cushion may be described by by the manufacturer as a flotation device, it is described more generally in this system as a "passsive pressure distributing" device. Only those devices designed to relieve local pressures are classified as the "pressure redistribution" type. "Active devices" are dependent upon a power source to change or distribute pressure.

The literature is replete with papers describing seating devices which, through clinical trials or patient testimonials, have claimed to reduce the incidence of pressure sores, or actually healed sores while sitting continues. Unfortunately there is a great variance in patient populations, and no one seating system has been found which meets the needs of all patients. This has been the experience of the author in seating clinics at OCCC, and has also been the experience in other seating clinics in North America, Mr. R. Holte, Rehabilitation Centre for Children, Winnipeg, Mr. Wallace Motloch, Children's Hospital at Stanford and Mr. Douglas Hobson, Memphis Tennessee, (personal communications).

The provision of seating requires the identification of specific needs and risks, and the selection or design of devices which best meet these needs. A recent review of the literature by Holley et al. (1979) describes general seating guidelines based on reports by Mooney et al.(1971) and Cochrane and Slater (1973), which recommend that: 1) shear forces be minimized, 2) devices be light and small for easy handling, 3) cushion life expectancy be at least six months, and 4) membrane or cover be absorbent, permit good air circulation, and be easily replaceable and washable.

Further specifications have been recommended primarily with respect to custom cut-out foam cushions. Rogers and Reswick (1974), indicated that fleshy anatomical sites are better able to distribute pressure than thin tissues overlying the bony prominences. He has correspondingly published maximum pressure guidelines for weightbearing anatomical sites, see Table 2.5. Similar guidelines have been adopted in other pressure clinics for the construction of foam cut-out cushions Manley et al. (1977) and Ferguson-Pell et al.(1980).

TABLE 2.5 MAXIMUM RECOMMENDED SITE PRESSURES

AUTHORS	ANATOMICAL SITES			
	SACRUM	ISCHIAL TUBEROSITY	GREATER TROCHANTER	PROXIMAL THIGH
Rogers (1974)	1,87 (14)	5,33 (40)	8,00 (60)	10,7 (80)
Manley (1977)	2,67 (20)	2,67 (20)	6,67 (50)	10,7 (80)
Ferguson-Pell (1980)	4,00 (30)	5,33 (40)	8,00 (60)	

PRESSURES kPa (mmHg)

TABLE 2.6 INTERVALS OF PRESSURE RELIEF

AUTHORS	TRIGGER TIME (min)	RESET TIME (sec)	RELIEF MODE
Fordyce (1968)	[contingent] 10 & 20	5 & 10	continuous
Patterson (1973)	[contingent] 10	4	continuous
Malavent (1977)	[contingent] 10	4	continuous
Temes (1977)	[contingent] 30	30	continuous
Black (1978)	[contingent] 15	60	accumulated
Roemer (1976)	[contingent] variable	variable	continuous
Chavala (1978-79)	[contingent] 10	20	continuous

The duration of pressure application is an aspect of sitting biomechanics which has been studied in connection with seat warning systems. These devices consist of a pressure or force (weight) transducer, such as a microswitch or pneumatic transducer, connected to circuitry which compares accumulated sitting time with preset periods of pressure relief. This information may be used to trigger warning displays when an empirical danger threshold has been exceeded.

None of the reported studies have dealt with the problem comprehensively as non-intrusive portable data loggers have not been available. Because sitting is a physical behaviour, time-warning experimental protocols should consider the following parameters:

1) Threshold pressures for activation of timer switches;
2) choice of contingent or non-contingent response in relation to presentation of warnings and subsequent carry over;
3) choice of lifting versus shifting to achieve pressure relief; and
4) identification of trained versus spontaneous body movements in conjunction with seating design.

These points demonstrate the complexity of studying this behavioural activity as well as the need for further rigorous studies. Table 2.6 displays the following parameters discussed by the authors of time warning studies: the sitting interval prior to warning (trigger time), and the reset time of pressure relief (continuous or accumulated relief).

The above demonstrates variations in approach to pressure relief. The critical factor remaining to be demonstrated for

continuous pressure re lief devices, is the establishment of a minimum duration of sitting time for ischaemic recovery. There are no references relating to tissue studies which specifically test this parameter, although Kosiak (1976) determined that tissue did not break down when pressures were cycled every 2.5 to 3 minutes. This represented a load-cycle of 30%. Keane (1978-79) indicated the time loading cycles safe for sleeping surfaces to be 2-3 hours for a minimum level of protection. However, he considered 20 minutes of ischaemia adequate to produce damage in muscle tissues, and recommended that mechanical beds turn patients at a rate of once in 4.5 minutes (eg. Roto Rest beds). He also reported that Oswald et al.(1963) calculated an average interval between major postural changes in normal sleeping subjects of 11.6 minutes. This interval was described by Keane as the minimum physiological mobility requirement. Consequently his reciprocating chair lifts the patient on and off the ischial tuberosities, every 9 minutes.

In Table 2.4, the loading conditions were used to classify seats into two groups; passive supports, dependent upon patient or attendant initiated pressure relief, and active devices, producing high pressures for controlled periods of time. The latter systems have adopted very conservative guidelines for the combination of pressure magnitude, duration and frequency. No comparable guidelines have been determined for patients using passive systems. For example, would the patient who lifts once every thirty minutes, require pressure relief for twice the duration of someone who lifts every fifteen minutes? Disease processes such as Polio, Multiple Sclerosis, and Arthrogryposis can produce a functional quadraplegia without the associated loss of skin innervation. Such people, although uncomfortable, often remain free of pressure sores on

rudimentary seating. Since they are physically only capable of shifting their weight, partial weight relief must be effective in protecting tissues during sitting where protective sensation provides the feedback to ensure the appropriate timing for the required body movements.

Skin temperature is another extrinsic risk factor which can be influenced by seating design. Under similar ischaemic conditions, the cooler support surface will reduce local metabolic rates and hence also the effects of ischaemia. There are no specific guidelines as to optimum surface temperatures, nor are there studies which correlate cushion temperature, blood flow and/or metabolic rates in skin. This parameter of seat design remains open for further study.

The last aspect of seating design relates to the mechanism of support or transferring load to flesh. It is discouraging that cushion developers do not describe the mechanical principles of their respective products. Descriptions such as"flotation" have little meaning and there is no accepted standard means of testing and classifying these devices.

Theoretical studies have been conducted with wooden, foam and gel models to identify deformation patterns around weightbearing bony prominences, Reddy et al. (1982). Bennett, in his series of papers discussing the transfer of load to flesh developed the following design concepts:

1) High shear stresses are found in tissue adjacent to the point of contact of a dull chisel (this condition simulates the internal stresses around the ischial tuberosity when one sits on a flat surface);

2) large stiffness gradients in the support surface, lead to correspondingly high internal shear forces in the tissue (the risk of trauma from support surface edges);

3) the ratio of shear to compressive stresses increases with decreasing tissue thickness;

4) support surface studies dealing with complex loading patterns should be developed from a combination of mathematical and experimental models; and

5) the optimum edge radius, with respect to minimizing shear stresses, is thought to be 12.7mm (0.5in).

Lindan (1965), conducted experiments to study sitting pressures on a controlled support surface, a bed of sprung nails at 1.4 or 2 cm. intervals. These data provided a pressure pattern related to this particular support mechanism and to no other. However, it did represent a reproducible surface. Significant findings included the changes in ischial pressures when the feet bore too much weight, (feet hanging/ 8,00kPa (60mmHg), feet elevated/ 13,3kPa (100mmHg)). When the subject's legs were free hanging, there was a significant unloading of tne ischial tuberosities. Modification of the support surface to simulate ischial cut-outs simply moved the high pressure gradients forward. However, it is difficult to know how well this model simulated such modified foam cushions. The study was the first of its type to simulate seating surfaces.

In summary, the complexity of seat design has been illustrated in this section, as evidenced by the number of parameters involved and by the divergence of opinion with respect to the critical values for individual specifications.

2.3.2 Studies of Interface Characteristics of Seating Systems Under Load

Many seating systems have been made commercially available in the last fifteen years. During this time, a number of evaluative studies have been conducted to measure one or some combination of the following parameters at the seat-patient interface, pressure, temperature, and humidity. Pneumatic pressure transducers have gained the widest use as a clinical tool. For convenience the transducers have been classified in terms of their operational physics and functional characteristics, see Table 2.7.

The functional characteristics of measurement systems are determined by the arrangement of transducers, and the associated information processing equipment. The transducers usually have tradeoffs in terms of calibration, frequency response, physical interference, specificity of response, and reliability.

2.3.2.1 Pressure Sensors:

The most common clinical pressure measurement tool now in use is the pneumatic type, with either a single or multiple cell format. The early design of the transducer permitted only single measurements of pressure; however, the addition of a feedback loop and air pump has made continuous measurements possible. Palmieri et al.(1980) compared pneumatic transducers with the electronic Kulite devices. The variability of the data for the pneumatic cells was 2-3 times less; however, reservations were indicated about relying on either device for estimations of absolute pressure. Those variables, contributing to variations in pressure tests, include subject to subject anatomical variations, seating system biomechanics, transducer positioning, and transducer mechanical

TABLE 2.7 PRESSURE TRANSDUCER PHYSICS AND FUNCTIONAL CHARACTERISTICS

	ELECTRICAL	MECHANICAL	CHEMICAL
ELECTRICAL	capac.(C) resis.(R)	strain-gauge(SG)	acid sheets (A)
MECHANICAL		pneum.(P) spring(S)	microcaps-ules (MC)

AND OPERATIONAL CHARACTERISTICS

	STATIC(-S)	DYNAMIC(-D)
POINT (P-)	(PS)	(PD)
SURFACE(S-)	(SS)	(SD)

TABLE 2.8 RESULTS OF PRESSURE STUDIES

AUTHORS	TRANSDUCER TYPE & OPERAT	REPORTED ERRORS	SEATING TEST RESULTS 1	2	3	4	5	6	7
Kostak (1959)	P - PS	·							
Weinstein (1965)				29,9 (224)	14,1 (106)			7,47 (56)	
Houle (1969)	P - PS	± 1,87 (14)			18,1 (136)	27,7 (170)	12,9 (97)	14,9 (112)	
Bush (1969)	C - PS								
Mooney (1971)	P - PS			18,1 (136)		14,9 (112)	18,1 (136)	18,1 (136)	21,9 (164)
Souther (1974)	P - PS	± 0,93 (7)	14,7 (110)	10,5 (79)			9,6 (72)	6,4 (48)	8,0 (60)
Garber (1978)	P - SS	± 0,93 (7)		10,5 (79)	10,1 (76)	12,8 (96)	13,1 (98)	10,7 (80)	
Lyddy (1978)	P - PS			15,7 (118)					6,4 (48)
Motloch (1979)	P - PS			13,6 (102)		8,8 (66)	12,3 (92)		17,3 (130)
Bowker (1979)			40,0 (300)	15,7 (118)				14,7 (110)	9,06 (68)
Holley (1979)	SG - SS			6,53 (49)				8,0 (60)	

Seating Codes: 1 - slung base; 2- foam, elastic; 3- foam, viscoelastic; 4- foam, contoured
5 - flotation, air; 6- flotation, water; 7- flotation, gel

Pressure Readings: The maximum report pressures are included and the errors estimates of measurement error not experimental range.

characteristics. Few investigators include careful assessments of these sources of measurement errors and not suprisingly cushion comparisons show large ranges of peak pressures, see Table 2.8.

The large subject-to-subject tissue and anatomy variations reduce the validity of predicting device safety from a pressure vs time tissue tolerance graphs, (see Figure 2.3). The most commonly tested device reported in the literature was the "Bye-bye Decubiti" cushion, with a pressure range of 7,10 kPa (53.4 mmHg) to 13,3 kPa (100 mmHg) under the ischial tuberosities. The various gel cushions ranged in pressure from 6,40 kPa (48 mmHg) to 17,3 kPa (130mmHg), and the foam cushions from 7,47 kPa (56 mmHg) to 21,95 kPa (165 mmHg).

2.3.2.2 Interface Temperature and Humidity Sensors:

In their reports of thermal testing of seating systems Ruch and Patton (1965), relate tissue temperature and metabolic rates. In most studies, thermistors were taped to the subject's skin at sites of both low and high pressures and monitored until an equilibrium temperature was reached. The factors which were considered most important in determining the interface temperature were, local blood supply and cushion insulation. It was found that highly thermal conductive materials, such as water, will introduce a large heat flux across the skin-cushion interface for a period of time, as determined by the thermal inertia of the system, (a large mass of water and/or tissue would take longer to heat than a small mass).

Brattgard et al.(1975), studied the temperature and relative humidity of comparative foam seats over a 90 minute period, concluding that the results were influenced by the subject's clothing, room temperature, pressure distribution and hygiene. The

temperature was depressed by reduced local blood flow, by reduced insulative properties of the cushion. A plastic network interface, placed on the support surface, succeeded in reducing the skin temperature by 5C° and the relative humidity by 30%. However, this study did not indicate whether or not the plastic network increased pressures under bony prominences.

Fisher et al.(1978) studied several types of seating systems for short periods of time (30 minutes) and observed that; foams caused temperature increases, gels produced no change and water cushions allowed a reduction in local temperatures. Interestingly, they also observed that high pressure sites changed less than those of low pressure, indicating the significance of reduced blood flow during the test period.

Although Fisher felt that most changes took place within the first fifteen minutes, Stewart et al.(1980) have followed temperature changes over a 120 minute period, measuring heat flux changes and surface moisture with humidial discs and electrohumidial sensors. They found variations which appeared to result from seating material and design properties. The covering material had a large influence on the relative humidity, with the nonporous materials, such as the membranes on the gel pads, generating the highest vapour pressures. These findings reflected the trends seen by the previous authors, suggesting that these characteristics may be more reliably described than the mechanical properties. However, seating systems should not be provided on the basis of these characteristics alone, but must also include consideration of the mechanical risks (pressure) to the patient. As these measures of interface conditions are indirect with respect to subsequent tissue viability, there remains a need for evaluation techniques, based on the individual patient's response to a particular system.

2.3.3 Properties of Seating Systems Related to Function and Utility

Although, in reporting test results of interface studies, many authors add as an aside that practical handling considerations are important in seat selection, the issue has not been dealt with systematically.

Mooney et al. (1971) recommends careful attention to such details as patient transfers and wheelchair propulsion, both of which require a solid reaction point for the user to maintain his balance. He found, in a survey of paraplegics, that maintenance of air pressures, fluid levels, leakage and cleanliness were major factors in user dissatisfaction.

Other factors mentioned by Motloch (1977), are support, comfort and management of spasticity. Spinal cord injured patients frequently have severe back pain which may be moderated by seat design. Enhanced respiration, and improved upper extremity function (a quadraplegic who "hooks" his arms to maintain the upright posture loses upper extremity function) can be achieved through the provision of appropriate trunk support.

2.4 TISSUE TRAUMA PROGRAMMES

2.4.1 Structure and Function of Patient Management Programmes

The existing tissue trauma progammes and pressure clinics are reviewed to demonstrate the significant differences between these and the progamme at the Ontario Crippled Children's Centre. Several types of programmes are mentioned in the literature: pressure sore prevention programmes for hospital wards, pressure clinics and general tissue trauma programmes. This research focuses on tissue trauma seating and the programmes of prime interest therefore, are the latter two types.

The programme reported at Rancho Los Amigos Hospital, Reswick and Rogers (1975), included both research and service programmes. Their protocol was as follows: patient screening by a pressure clinic, pressure test assessments, the development of seating guidelines through basic and applied research, reinforcement of the patient's pressure sore awareness, and participation in a recall programme to maintain the individual's pressure sore prevention regimen.

The pressure clinics at the University of Strathclyde, Ferguson-Pell et al. (1980) and the Conradie Clinic in South Africa, Key et al.(1978-79) have similar goals, with varying degrees of contact with the overall programme of the individual patient. All three of the above groups have developed a primary approach to the provision of seating by custom modifying foam seats. This includes a systematic approach to measuring, fitting and cushion evaluation by pneumatic pressure transducers. Angell and Vistnes (1980) have identified the need to take a holistic approach in pressure sore prevention by mixing information from a number of measurement systems with careful patient assessment.

The programme at the Ontario Crippled Children's Centre, Hahn and Black (1977) had its own caseload on referral from both paediatric rehabilitation clinics and adult rehabilitation centres. A wide variety of seating systems were considered for each patient with no single seating system dominating the clinic. In addition, new seating systems developed in the department or obtained from external sources, were considered for evaluation.

2.4.2 Impact of Pressure Clinics

The tissue trauma programme at Rancho Los Amigos reported on the incidence of pressure sores, correlated to the pressures measured under critical sites, Ferguson-Pell et al. (1980), indicating that prolonged redness was observed at pressures of 40mmHg. and that there was a large increase in the incidence of pressure sores at pressure of 70mmHg. Optimal pressure ranges for the sacral, ischial, hip and thigh weight bearing areas were determined through clinical experience; however, this did not include long term studies to describe in more detail the success of pressure sore prevention, although the later studies in South Africa indicated that 89% of their patients remained pressure sore free over a period of two years. The Strathclyde programme demonstrated a drop in incidence of pressure sores from 10% to 3.7% over a two year period.

Clinical programmes of this type must play an integral role in the application of tissue trauma research, and for this reason there is a strong overlap in research and service within the programme at the Ontario Crippled Children's Centre.

2.4.3 Tissue Trauma Programme at The Ontario Crippled Children's Centre

The Tissue Trauma Programme at the OCCC between 1975 and 1980 followed over 100 patients with chronic pressure sores who progressed to a sore free lifestyle, subsequent to receiving protective seating. The provision of such seating was the result of the following process: assessment, prescription, provision and evaluation as illustrated by the patient flow diagram, see Figure 2.3.

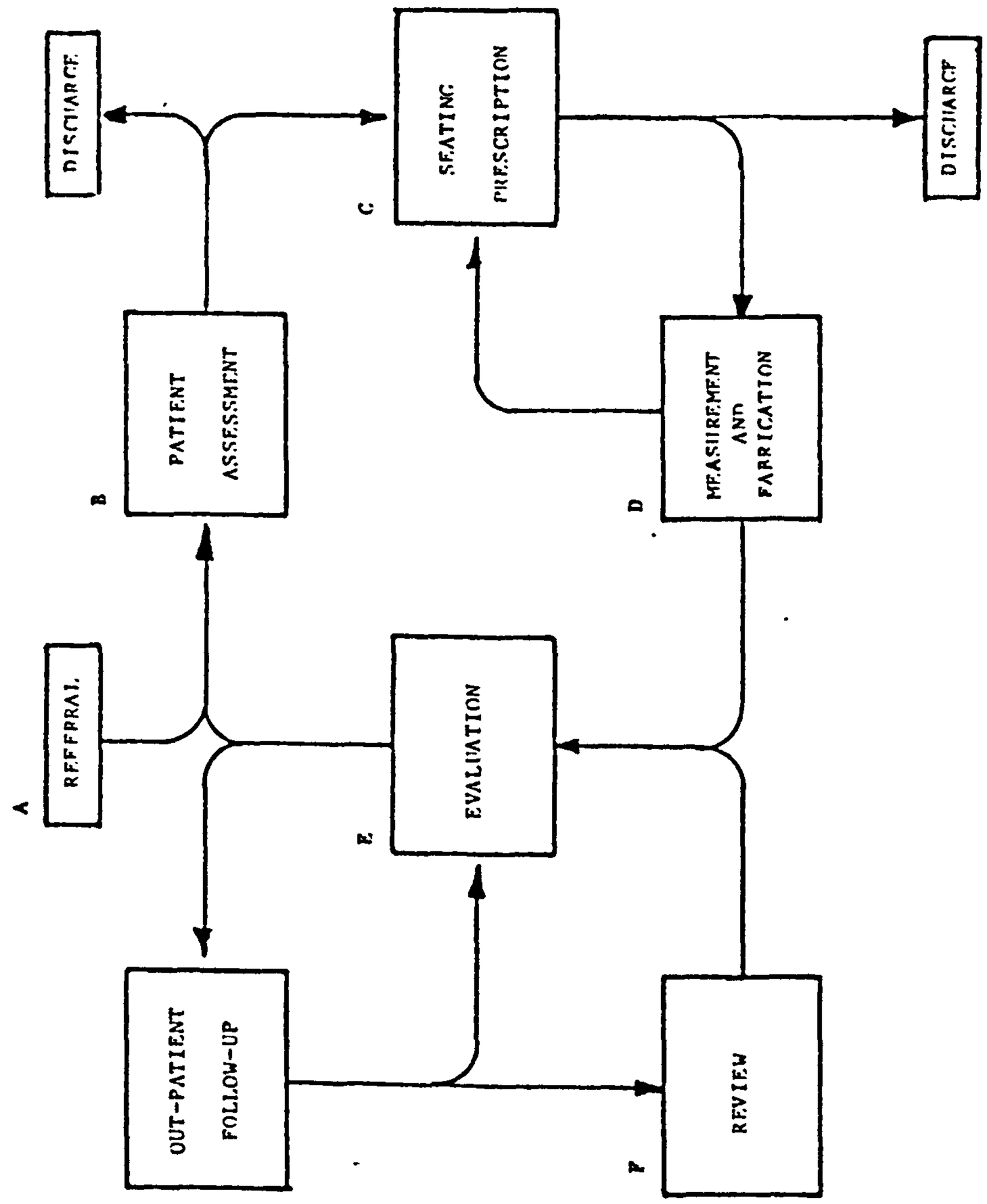


FIGURE 2.3 SEATING PROCESS

To obtain an initial referral (A) to the Tissue Trauma Programme a pressure sore risk had to be identified within the patients' regular medical follow-up . A combined assessment (B) involving medical, therapy, psycho-social and biomechanical investigations, was the first phase of the seating process. A team work approach was taken to develop a complete profile of intrinsic and extrinsic pressure sore risks for presentation in the clinic , see the sample risk factor sheet in Appendix III. Biomechanical tests included an edgelighted glass table sitting examination, single cell pneumatic pressure measurements over the ischial tuberosities and greater trochanters, and thermography of the subject's skin before and after prolonged sitting.

The seating goals were jointly defined in the tissue trauma clinic (C), and a prescription prepared, defining the technical requirements of the new seat. In the process of filling the prescriptions, dynamic pressure measurements were used to determine whether or not it was possible to meet the seating specifications outlined in the clinic (D). If not, the prescription was returned to the clinic or physician for alteration. Once the prescriptions' criteria were fulfilled, the patient was evaluated on the new seating system thermographically, to determine whether improved protection had been achieved. Therapy assessments were conducted to ensure that design changes did not interfere with daily functional requirements such as personal mobility. The tissue evaluation (E) provided a short term prediction of the patient's safety and, later, a long-term review (F) to detect any changing risk.

The tissue evaluation was the unique and critical element in this process. The rapid feedback of potential success or failure of the seating system provided a closed loop in the seating design

process. The more specific this evaluation, the more rapidly safe solutions could be found for high risk patients.

It is the hypothesis of this research that dynamic monitoring of tissue physiological reaction to test sitting is the most direct, non-invasive approach to support surface evaluation, and further, that thermography is the best available tool for this task.

2.5 SUMMARY OF PRINCIPLE ARGUMENTS

The following points describe the conclusions drawn from the literature and the logical steps which led to the research programme reported in this report.

1) Repetitive low pressures appear to be the predominant cause of pressure sores attributed to prolonged wheelchair sitting. The mechanism of necrosis is reversible up to and including the stage of superficial ulceration.

2) Those elements which describe a patient's tissue risk include both intrinsic and extrinsic factors. These were described with respect to their influence on the magnitude, duration, and frequency of loading as well as the resistance of the tissues to the ischaemic conditions. This author expressed the view that the psychological or behavioural risk factors operated on the physical disabilities of the individual patient.

3) Periodic relief of external pressure and early detection of reversible tissue damage appears to be the critical element in successful regimens of self care.

4) Seating systems were thought to be capable of reducing the physical risks of developing pressure sores by moderating high pressure or shear stress gradients. Changes in the structure and/or support materials can alter the distribution and relief of stresses in the patient's tissue.

5) Tissue tolerance guidelines as developed through authors such as Husain, Kosiak, Dinsdale, and Rogers have been applied in Pressure Clinics to monitor the fit of contoured seats. However, all of the pressures recorded for any such systems represent combinations of pressure and duration thought to produce microscopic changes in tissue.

6) The seating systems were classified in terms of their support mechanics, (active or passive) pressure (distribution or redistribution). The majority of commercial cushions are intended to maximize pressure distribution through the properties of the materials but the results of evaluative studies demonstrated widely varying values for maximum pressures.

7) The pressure transducers most commonly used in pressure clinics are pneumatic and when used to aid custom contouring foam cushions have claimed good results. The measurement of such interface pressures has not produced adequate results, in that there is considerable variation between authors testing the same seats and wide variations within sets of readings from the same study.

8) Although times for pressure relief have been empirically estimated at 30% duty cycle, there is little research dealing with this specific problem in detail. Several warning systems have been experimented with, but in insufficient detail to bring forward objective data related to tissue tolerance.

9) The complexity of matching patients with seating system necessitates the involvement of a multidisciplinary team to assess and test the individual with the appropriate system. Within the context of such a programme, the seating is seen as a process with evaluation playing a dominant role in its completion .

CHAPTER 3 THERMOGRAPHY: A METHOD OF MONITORING TISSUE RESPONSE TO ISCHAEMIA

3.0 INTRODUCTION

This chapter presents a rationale for selecting thermography as a tool for evaluating the state of health of weightbearing tissues. The pathological consequences of ischaemic insult to such tissues are reviewed, identifying measurable states of change which reflect upon the tissues' quality (empirically defined by the two parameters: permanent structural changes -Tissue Type-, and transient changes, -Tissue Condition).

It will be shown that changes in skin temperature have been associated with the magnitude and duration of test loading, and that the thermograph is the most practical available instrument for clinical application. The variety of factors influencing both thermographic measurement and interpretation is discussed.

3.1 DETECTION OF TISSUE TRAUMA

3.1.1 The Ischaemic Process

Ischaemia can gradually produce irreversible pathological tissue changes. This section describes those tissue changes which can be monitored through clinical observation, or by histological techniques. If tissue quality, or deterioration, can be consistently quantified, it should be possible to evaluate seating systems for the individual patient. This would be achieved by recognizing healthy or unhealthy responses to the stresses induced by sitting. This concept was introduced into clinical practice by Brand (1971), with respect to the management of insensitive feet, and in other centres, such as Rancho Los Amigos Hospital, for the evaluation of bed surfaces, Reswick and Rogers (1976). Techniques

for assessing tissue quality are based on either measurements of symptoms, or by direct histological study of biopsy samples, which may pose a physical risk to the patient. Only indirect, non-invasive techniques are apt to be clinically acceptable for routine use.

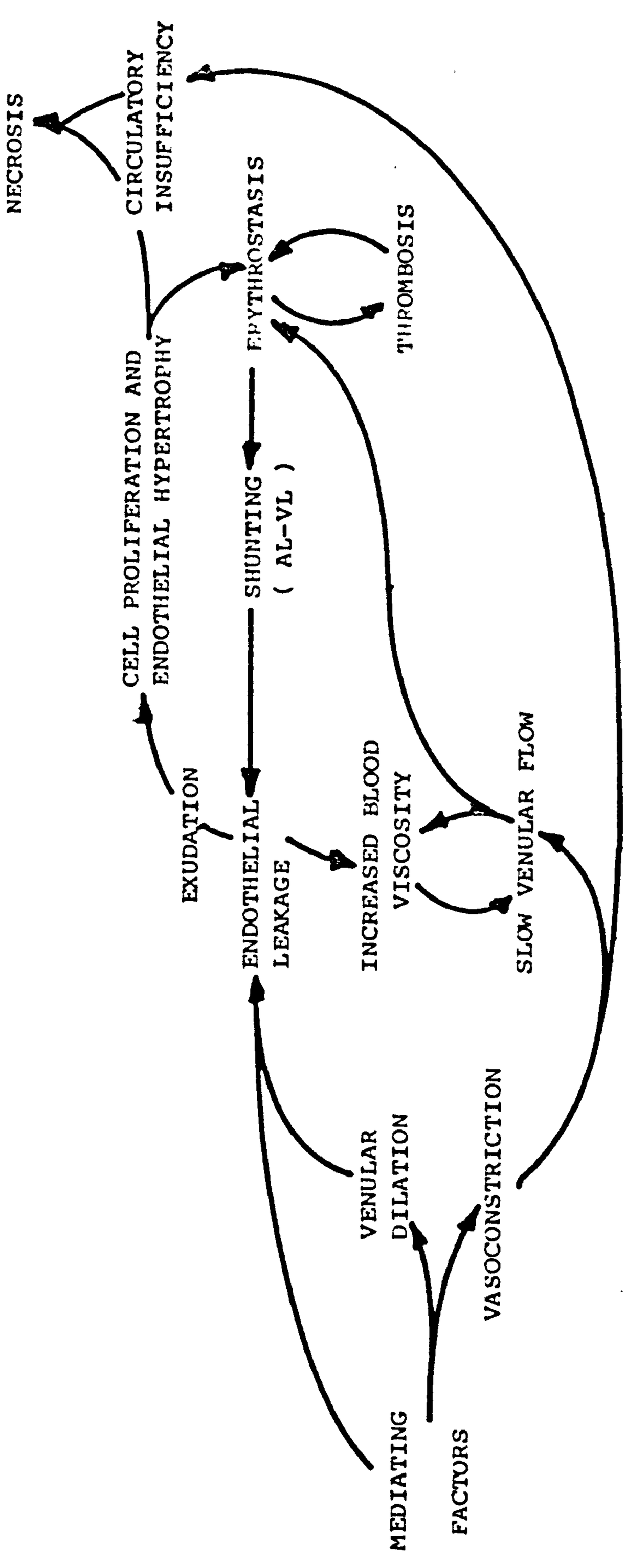
The process of tissue breakdown is described in diagrammatic form, figure 3.1 (Kulka 1964). This model is based upon changes in blood flow, which are the result of a progression of vascular responses to chronic inflammation, which in turn leads to local circulatory insufficiency.

Two loading conditions lead to necrosis: single applications of pressure, (prolonged ischaemia), and recurrent applications of pressure (brief ischaemic periods of tolerable duration). It is the accumulative nature of the ischaemic process, which plays the predominant role in the formation of pressure sores for the wheelchair bound patient. Clinically, it is known that these sores develop over weeks or months of repetitive sitting and, as such, follow this inflammatory model described by Brand, (1979) as a form of autolytic necrosis. He described a process in which the inflamed tissues gradually become saturated with new cells full of lysosomal enzymes, and hence susceptible to sudden necrosis through a chain reaction of cellular digestion, when triggered by some traumatizing event. This type of necrosis usually starts deep within the tissues, and later breaches the skin, precipitating an ulcer.

3.1.2 Pathological Signs and Symptoms

The five signs and symptoms of acute inflammation are: calor (temperature increase), rubor (redness), tumor (swelling), dolor (pain), and functio laesa (loss of function). Under the conditions

FIGURE 3.1 INTERMEDIARY MECHANISM OF INFLAMMATORY TISSUE DAMAGE: A TENTATIVE SCHEMA



Mediating Factors: Neural, Hormonal and Hemic

Reference: Kulka, (1964) "Microcirculatory Impairment as a Factor in Inflammatory Tissue Damage"; Ann. New York Acad. Sci.,116, 1018, 1964

of low grade inflammation and insensitive skin, these symptoms are reduced to calor, rubor and tumor. The first two signs are due to changes in vascularity, and the third, to the presence of local cellular exudate and oedema.

Goller et al.(1971) has described the interrelationship of skin colour and temperature as seen in Table 3.1 .

Brand (1971) described changes in tissue texture and tension associated with inflammation, and discussed the possibility of measuring associated changes in mechanical impedance with a visco-elastometer. Rats were exposed to simulated excessive walking stresses. Their footpads became inflamed and the tissues were observed to deteriorate when there was inadequate recovery time between successive trials. However, with adequate relief, the tissues hypertrophied, increasing their tolerance to such stresses. Similar histological studies could not be conducted with patients for ethical reasons.

Inflammatory changes should be distinguished from transient hyperaemic responses which follow short periods of ischaemia. One distinguishing factor between these two tissue states is the persistance of localized increase in blood flow. The hyperaemic reactions are reversible, and short term, described by Roemer (1980 and 1981) as having a rapidly disappearing pink flush and a transient increase in temperature after relief of loading. Nursing instructions commonly include the guideline that a hyperaemic flush should be expected to persist for half of the duration of the ischaemia.

3.1.3 Measurement of Symptoms

Certain characteristics are essential for any measurement system which is to function as an evaluative tool in the clinical

TABLE 3.1 INTERRELATIONSHIP OF SKIN COLOUR AND TEMPERATURE

SKIN COLOUR

VASCULAR STATE	PALE	RED	BLUE	
Arterioles Constricted	Ischaemic conditions	Cold ambient environment no dissociation of oxy-haemoglobin	Venous stagnation	(cool)
Arterioles Dilated	arterial venous shunts	Good circulation and blood supply		(warm)
	Capillaries Constricted	Capillaries Dilated (oxygenated)	Capillaries Dilated (deoxygenated)	

SKIN TEMPERATURE

(Killian 1959, described the subsequent relationship between skin colour and temperature after hypothermic injury)
Skin Colour: depends upon the amount of blood in the capillaries and the oxygenation of blood in minute vessels.
Skin temperature: depends upon the blood flow, determined by the condition of the arterioles.

TABLE 3.2 MEASUREMENTS OF TISSUE PATHOPHYSIOLOGY

SYMPTOM	MEASUREMENT MEDIUM	INSTRUMENTATION
Calor	surface temperature tissue temperature	theromography thermistor
Rubor	light reflectance blood flow	photography laser doppler radioisotope
Tumor	volume change shape sensing mechanical impedance	plethysmography moire fringe viscoelastometer

setting. The assessment of tissue response to wheelchair sitting must take into account parameter, such as permanent tissue changes (scarring), transient tissue states (inflammation), and accumulated loading conditions (ie. the dynamic loading of the supporting tissues throughout a day of sitting). Ideally, the measurements should be quantitative, so that statistical techniques can be applied to determine trends and guidelines. As mentioned previously, the visible signs of the inflammatory process, are calor, rubor and tumor. Measurement systems which have been used to detect these symptoms are listed in Table 3.2 .

The location and shape of surface textural changes, such as surgical scar sites, may be recorded photographically, but local blood flow cannot be reliably deduced from skin colour, Adamson (1978). Laser doppler techniques now show promise for direct non-invasive localized measurement of skin blood flow, but they do not allow for scanning of large surface areas. techniques. Radioactive washout could not be conducted clinically with subjects sitting immediately prior to the test. Newson et al. (1981) correlated skin surface oxygen levels ($P_{s}O_{2}$) with externally applied pressure to evaluate this technique as an indication of capillary blood flow. Large variations in the initial $P_{s}O_{2}$ values and the applied pressure required to produce anoxia at the skin surface were found. Thermal measuring techniques provide indirect information on blood flow, and imaging systems, such as the thermograph, scan the full support surface, buttocks and proximal thighs, simultaneously.

3.2 THERMAL STUDIES OF PRESSURE ON TISSUE

3.2.1 Objectives of Thermal Studies

This section reviews those research programmes which have sought to quantify tissue reaction to pressure induced ischaemia, and presents the subsequent direction taken by this research programme in the fitting of wheelchair seats, orthotic and prosthetic weightbearing surfaces and chronic care beds.

Based on the applications listed in Table 3.3 below, several research goals are most commonly sought. The research projects are discussed in two groups: those using pressure testing probes, and those evaluating support surfaces. The probe trials apply controlled pressures by means of an indentor instrumented with thermistors, which record temperatures during, and immediately after, test loading. Although skin temperatures may also be detected during and immediately after sitting by skin contact thermistors, the point of application must be determined prior to any examination. Table 3.4 summarizes the contributions of the major investigative teams to developments in this field.

3.2.2 Localized Loading Studies

The end product of all basic tissue trauma research is the development of a foundation for understanding the risks faced by the individual patient when choosing a support surface, such as a wheelchair seat, or a pair of custom shoes. Experiments, applying pressure to small areas of skin, contribute to this general goal by determining how individual units of tissue behave under fairly well defined conditions. A second possible area of application for these techniques might be in the classification of skin type. If there are varying types of skin reactions, identifiable by such

TABLE 3.3 OBJECTIVES OF THERMAL STUDIES

I Stress Correlation (Magnitude and/or Duration of Loading These studies seek correlations between skin temperature fluctuation and loading conditions, Rogers (1973) and Roemer (1976 and 1979).
II Stress Correlation (Pattern of Loading) Temperature imaging systems have been used to study the effects of weight-bearing surfaces, to identify high risk sites and to provide guidance in shoe modification Brand, (1972).
III Tissue Quality (Risk Assessment of Tissue) These seek to identify variations from baseline skin temperatures or load responses which characterize the health of the tissues. Brand (1971) and Black (1980).

TABLE 3.4(A) INVESTIGATIONS OF PRESSURE ON TISSUE AND SKIN TEMPERATURE

Authors	Techniques	Significant Findings
University of Virginia Lewis (1972,3,8) Goller (1971,3,6) McLaughlin(1971,6) Verhonick (1972) Trandel (1975)	-pressure probe -thermography -multiple body sites -prone support surface tests -human subjects	1) The hyperthermic response after pressure relief followed by a temperature decay was described; 2) a subjective correlation between the magnitude and duration of the applied load with the magnitude and persistance of the hyperthermic peak was postulated; and 3) skin temperature "flares" were seen to correspond with high pressure sites on the support surfaces.
USPHS Carville and Louisiana State University Brand (1969,71,75) Bergtholdt(1975,9) Burke Sabin Shipley (1979) Thompson Harris	-cyclic loading -thermography -rat foot pads -human feet, Hansen's disease -footwear, plastazoate molded sandals -histology -mechanical impedance (viscoelastometer)	1) The accumulative effects of repetitive stresses, conditioning of tissue increasing its susceptibility to necrosis by the release of autolytic enzymes; 2) inflammed tissues were identified by high local skin temperature and this information used to assist in modifying footwear or traumatizing activity; and 3) relative temperatures were found to be more significant than absolute temperatures.

TABLE 3.4(B) INVESTIGATIONS OF PRESSURE ON TISSUE AND SKIN TEMPERATURE

Authors	Techniques	Significant Findings
Rancho Los Amigos Hospital Reswick (1973) Rogers (1974 & 5)	-thermistors and thermography -pressure probe (Tempress Unit) -multiple body sites -differential temp. readings (apx. gradients) -prone and sitting surfaces	1) Hyperthermic response after release of load; 2) thermal "rebound" during cooling; and 3) the significance of measuring several locations simultaneously, "differential temperature", similar to relative temperature measurements.
U.C.L.A., Santa Barbara Memorial Rehab. Foundation Centre Roemer (1976) Mahanty (1979)	-thermistor and closed loop const. pressure probe -human subjects, various sites -mathematical modelling of thermodynamics	1) Observation of transient temperature rise after pressure release; 2) the duration of the stress showed a correlation with the transient increase in temperature; and 3) fitting subject data to a biotherm model, this was the first analysis based on such an approach.

TABLE 3.4(C) INVESTIGATIONS OF PRESSURE ON TISSUE AND SKIN TEMPERATURE

Authors	Techniques	Significant Findings
Nunnery Fields Hospital Barton,A.A. (1973) Barton,M.	-thermography -multiple body sites (healing pressure sores -serial observations -differential temperature	1) Classification of tissue in various pathological states based on passive thermal behaviour; 2) increased local blood flow (for healing) resulted in a +2.5 increase in local temperature; and 3) temperature differential between high blood and insufficient flow +6C° (possible shunting of blood flow).
University of Aberdeen Pye, (1976) Bowker (1976)	-Thermistor and perspex indenter -thermography -various sites human subjects -mathematical modelling	1) Large variations in finger temperature subject to many external and internal influences; 2) hyperthermic rise after pressure removal peaked at five minutes; and 3) finger date matched heat flow model.

tests, it should be possible to assess individual skin risks with some accuracy.

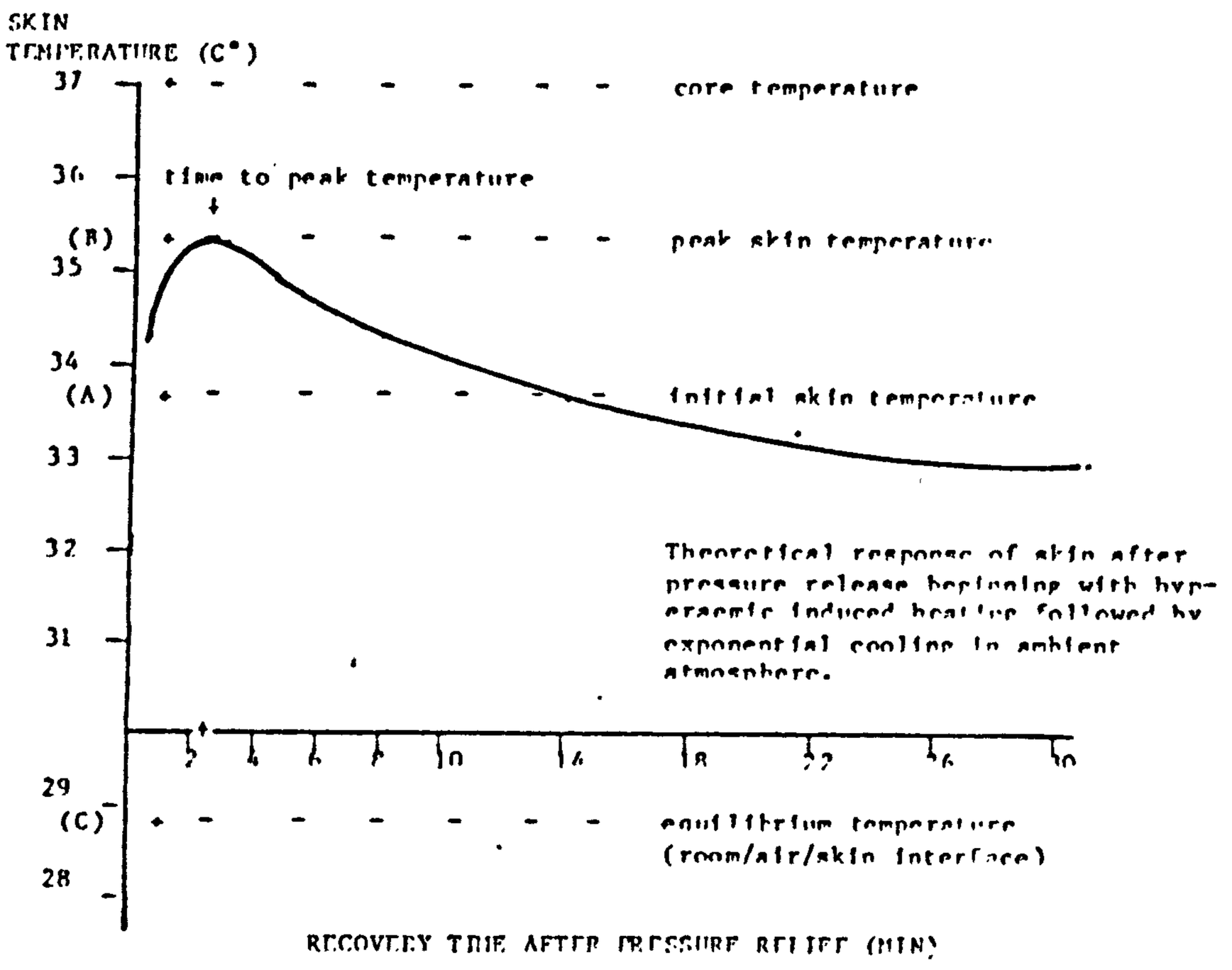
Prior to discussing the general results of the probe studies, it should be emphasized that there has been a continuous evolution of the associated instrumentation, giving rise to conflicting results in the literature. There are three characteristics of a generalized skin cooling curve which can be measured see figure 3.2; (A) the initial temperature after pressure relief, (B) the magnitude and duration of any hyperthermic response, (C) the cooling decay and its final equilibrium temperature.

The initial skin temperature immediately after pressure relief (A) has not been considered a reproducable measure, because the predominant variables are determined by such extrinsic influences as the insulative effect of the cushion, and the time required to reach an equilibrium temperature between the user and the cushion.

Those studies, in which the pressure probe included a contact thermistor, recorded skin temperature changes during loading, thus establishing an accurate initial cooling temperature. Consider point (C), in Figure 3.2; theoretically there will eventually be an equilibrium skin temperature between ambient and core temperature. Rogers (1973), followed skin temperature for up to three hours after loading, and described a rebound phenomenon, marked by large variations in skin temperature over a period of several hours. This trend has not been observed by other investigators, although they have not collected measurements over such a long time period.

The consensus of opinion between Goller (1976), Rogers (1973), Roemer (1978) and Pye and Bowker (1976), is that there exists a correlation between loading conditions (magnitude and duration), and

FIGURE 3.2 SKIN TEMPERATURE RESPONSE TO PRESSURE RELIEF



subsequent increases in skin temperature upon the release of external pressure. The data in Table 3.5 support this, but the only Roemer and Mahanty (1978) applied statistical analysis techniques to their data. They concluded that the duration of stress was correlated to the applied load at a 5% level of confidence. Another useful finding of this study was the minimum distance from the probe, where no thermal disturbances were noted. Thermal gradients disappeared at a radius of 6 cm from the test site, implying that thermal anomalies adjacent to bony prominences are evidence of ischaemia displaced from the anatomical bony prominence. This might be caused by the gradient of shear stresses in the tissue, generated by the point loading pattern.

Brand (1971) has applied cyclic loads to rat foot pads with a mechanical probe. These experiments were designed to simulate the repetitive stress of walking. The cyclic loading produced changes in tissue state, which were identified histologically. The skin temperature was monitored and fluctuations observed which were entirely different from those reported in the single load tests. Elevated temperatures were sustained for prolonged periods as inflammatory states were reached. There was no identification of critical absolute temperatures related to specific morphological changes. However, contra-lateral temperature differences for weight bearing sites of (1-5C°) were thought to be significant, Bergtholdt (1979). Known sites of inflammation were observed to have local, relative increases in temperature of up to 10°C. This model of repetitive loading was recently modified to simulate sitting conditions, through the application of low cyclic pressures on pigs. The preliminary results have shown the same pattern of skin response as that described for rat foot experiments.

TABLE 3.5 SPECIFIC RESULTS OF SKIN TEMPERATURE EXPERIMENTS

Author	Loading Conditions			Initial Temperature	Peak Response		Cooling Response		Other Comments
	Pressure kPa	(mmHg)	duration (min)	Probe Temp. (C°)	ΔTemp. (C°)	time (min)	Δtemp (C°)	time (min)	
Goller et al. (1976)	20,0	(150)	10	1	1.9	1	0.0	1.0	Sample individual graphs with no statistics. Results for subject 4. - forearm test site
	20,0	(150)	10	1.8	3.1	1	1.3	1.0	
	34,7	(260)	20	2	2.3	1.8	1.2	10	
	34,7	(260)	29	2.8	4.0	1.8	1.2	10	
Rogers and Reswick (1973)	16,0	(120)	180	4.5	5.1	160	2.0	180	trochanter, taken from graph 5.15. 4 RLAH Report 1973
	16,0	(120)	160	4.5	4.8	15	0.5	120	
Roemer (1979)	13,3	(100)	45	0	0.1	4	-0.2	15	Samples from Figure 3.7, trochanter
	13,3	(100)	67	0	0.6	4	0.1	15	
Pye and Bowker (1976)	19,0	(143)	20	.5	1.3	.5	---	20	fingers and forearms,
	28,0	(210)	20	.1	.7	1.0	---	20	
	----	---	20	.5	1.0	2.0	---	20	

3.2.3 Support Surface Studies (Complex Loading)

The second type of study deals directly with subjects using support surfaces. The investigators monitored skin response over a large contact area. Thermistors have been used for this type of study, either with a single transducer placed at a point of interest, or with a network monitoring a number of chosen sites simultaneously. Using thermography, the investigator can monitor surface temperature patterns over large areas of skin after the trial period of sitting.

Dr. Brand's team at USPHS, Carville, has been applying thermography on a regular basis in orthopaedic clinics. The main goal of this programme is the prevention of pressure sores in patients with Hansen's disease (Leprosy). Thermography, when used as a screening tool, scans large areas of skin to locate small foci of inflammation or infection. Once such damaged sites have been identified, the team investigates the patient's daily activities to determine the source of trauma.

Resolution of the risk site may require special training, education and equipment. Typically, the most severe risks relate to poor footwear. Custom sandals are often constructed to redistribute the forces away from threatened bony prominences. Thermography is also used to monitor the patient's skin temperature after trial use of the new device. The criterion for success has been increased cooling rate of the high risk sites after comparable stresses, on subsequent examinations (an improving trend).

In other studies, such as those conducted by Verhonick et al.(1972) and Trandel et al.(1975), thermal flares were observed at the sites of maximum pressure in subjects lying on bed surfaces with

nylon sheets. There were no quantitative data included in these reports.

3.2.4 Selection of Instrumentation for Clinical Studies

The research programme at OCCC was constrained to introduce measurement techniques which would provide useful data for the seating programme. Thermal patterns were expected to provide rapid identification of high risk sites. Subsequent seating modification, expected to reduce the local pressures at these sites, were subsequently to be evaluated by documenting changes in isotherm patterns. Thermography appeared to be clinically practical; however, it was considered essential to introduce quantitative techniques.

Instrumentation was sought to meet the following objectives:

1) to display both absolute and relative skin temperature data;
2) to present such data in a clinically understandable form, for use by engineers, therapists and physicians; and
3) to collect these data in such a way as to be safe and acceptable to the individual patient.

These requirements have been most closely met by the thermographic systems which are commercially available. The physics underlying these devices has been reviewed by; Cobbold (1974), Wallace and Cade (1975), Poole and Tolwijk (1976), Adamson (1978) and Stillwell (1981).

In brief, several of the significant principles are presented graphically, in Figure 3.3. The spectral radiant emittance is shown for an ideal "black body" surface. The solid curve represents the emittance as a function of wavelength, Planck's equation, with a maximum amplitude at approximately 9 microns wavelength for a

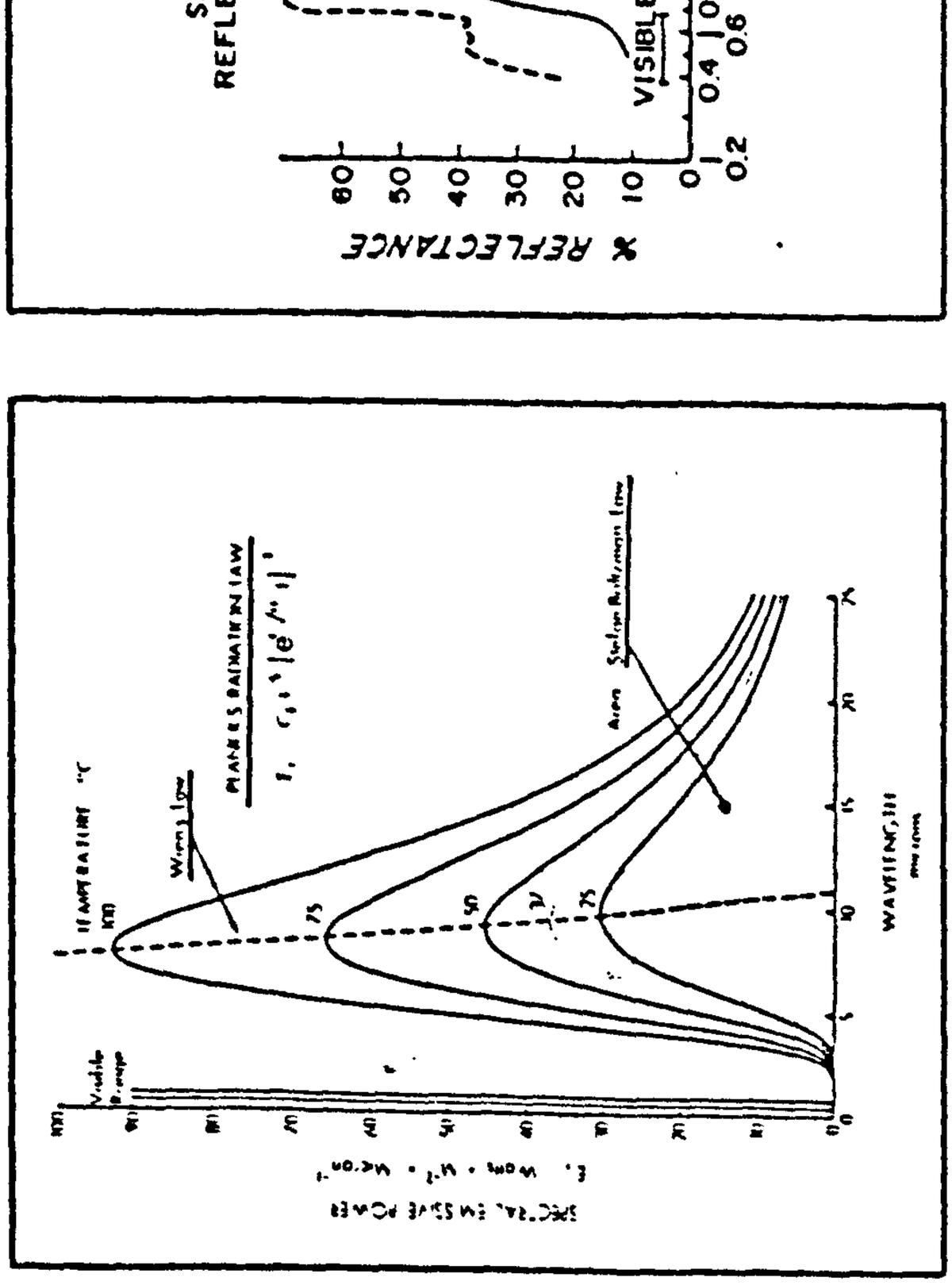


FIGURE 3.3 ENERGY DETECTED BY INFRARED THERMOGRAPHS

Spectral reflectance of human skin, and thermal emission spectrum of a black body at skin temperature.

Reference: Poole, D.O. and Stolwijk, J.A.J. (1972) Chapters in: Medical thermography, theory and clinical applications. Uematsu S. ed.: Los Angeles, Cal: Brentwood Publ Corp.

Plank's radiation law relating the infrared emission to the wavelength of the radiation.

temperature source at 300 K. The broken curve indicates the percentage of the total radiant energy emitted at any given wavelength. A second set of considerations, pertaining to the operational characteristics of the detector and of the atmosphere, are presented in the top section of Figure 3.4.

The transmittance of infrared radiation through air is a function of its wavelength with resultant windows of low attenuation. An ideal detector should operate within a range of wavelengths where significant quantities of energy are radiated from the source, and at wavelengths corresponding to the transmission windows. In addition, the detector must be sufficiently sensitive that changes in incident energy levels can be detected. This detectivity is also indicated in the same figure as the transmittance for indium antimonide (InSb), and cadmium-mercury-telluride (CdHgTe). These are two examples of photon detectors used in high speed systems. It can be seen that only a small portion of the emitted energy is detected . As a result of the extreme sensitivity of these high speed detectors, such as InSb, liquid nitrogen cooling is required to screen out all the ambient infrared radiation except that focussed through a set of germanium lenses (infrared radiation does not transmit through glass).

The presentation of such information was thought to be most readily appreciated in the form of either a grey scale, or colour image. The clinician or therapist could learn to identify anatomical sites, and, when reviewing the data, to associate high risk sites with the design of the patient's seating system. Pure graphical or quantitative data are more difficult to interpret.

The instrumentation system poses no hazard to the patient. For example, detectors worn against the skin during sitting might

increase the local pressure and precipitate tissue trauma. Thermography is a remote sensing device, requiring only proper exposure of the patient to ambient, atmospheric conditions after a period of sitting.

3.2.5 Choice of Thermographic Systems

The selection criteria were based on both the technical specifications and on the clinical demands. The most common system available at the initiation of this research, was the AGA 680 system. The backup service programme was well organized locally, and the company was prepared to assist in the early pilot programme by the lending of equipment. The other attractive aspect of this system was the colour monitor, which facilitated the identification of temperature patterns, permitting quantitative measurement of relative temperature differences. Thermographic imaging may be achieved through several types of technologies, indicated in Table 3.6.

The pyroelectric vidicon system will probably become the predominant tool of the future when it detects infrared radiation with wavelengths between 1 and 10 microns. Stillwell (1981) suggests that solid state detectors (platinum doped silicon) constructed in high density focal plane arrays may also make low cost thermographs possible.

Image analysis through pattern recognition techniques will play an important role in automatic thermographic analysis. Standard video processing techniques, existing hardware and pattern recognition software packages may be used with thermograph scan converters to enhance the use of such analytic techniques. As more is understood about specific applications of thermal sensing, the

TABLE 3.6 THERMOGRAPHIC IMAGING SYSTEMS

Liquid Crystal (temperature sensitive cholesteric crystals)	a) spray application b) encapsulated, flexible sheets for contact thermography
Film (infra-red)	grey scale film, not sensitive in the optimum area of the spectrum
Hybrid Film (polaroid)	an infra-red detector driving a superimposed LED temperature profile
Radiometers	detectors driving a digital read out of remotely sensed temperature
Pyroelectric Vidicon Camera	infra-red sensitive vidicon tube which generates a standard video image, Shephard (1977)

greater the possibility that effective use could be made of simpler detection systems, such as thermistors or liquid crystals.

Microwave thermometry provides the opportunity to sense temperature sources within the tissues; however imaging remains a severe technical challenge, Leroy (1982).

3.3 INTERPRETATION OF THERMOGRAPHS

3.3.1 Measurement Errors

The author's direct experience is with the AGA 680 medical thermograph. Those comments based upon personal experience will relate to this specific instrument. The infrared patterns displayed by a thermograph are clinically considered representative of skin temperature. Young (1970) refers to terminology, proposed by Davies (in personal communication), which specifies the description of thermograms as records of Infra Red Emission (IRE) and not of skin temperature. However, the discrepancy between detected IRE and skin temperature can be calculated.

The total power radiated over all wavelengths, (W), has been described by the Stephen Boltzmann equation, Gershan-Cohen et al., (1966).

$$W = \varepsilon\sigma\ T^4$$

where: ε - denotes emissivity

σ - denotes the Stephen Boltzmann constant

In addition, Hardy (1939) has shown skin to be a nearly perfect absorber and emitter of infrared energy, ($\varepsilon = 0.989 \pm 0.01$). Therefore, the observed heat flux very nearly represents the actual skin temperature.

Another source of error is the apparent drop in temperature for surfaces not normal to the camera. Such geometrical effects have been studied with respect to the dependence of surface emissivity on the viewing angle. Watmough, (1970), Lewis et al.(1973) and Salter (1976) all agree that apparent surface temperature does not seriously change, <1C°), until the viewing angle is greater than 70° - 75°. If the examination pertains to highly curved portions of the surface anatomy, it will not be possible to directly obtain measures of thermal gradients. The thermograph display only presents a normal projection and hence distorts spatial data.

The examination environment, in terms of ambient temperature, relative humidity, and draughts, is directly involved in a subject's thermodynamic equilibrium, and subsequent skin temperature. Stolwijk (1976) has summarized this in the following relationship:

$$S = M - (\pm W) - E - R - C$$

S = Rate of heat storage (watts)

M = Rate of metabolic heat production (watts)

W = Mechanical work (watts)

E = Rate of evaporative heat loss (watts)

R = Rate of net radiant heat transfer to or from the environment (watts)

C = Rate of convective heat transfer to or from the environment (watts)

Several conclusions which bear on thermographic techniques were drawn on the basis of subsequent derivations from Planck's equation:

1) The ambient temperature should be close to that of the subject's (306 K), to minimize the mean radiant transfer with the environment (R);

2) evaporative heat losses are from both respiration and water evaporation at the surface of the skin, with the latter having a maximum loss when the skin is just dripping wet; and

3) the convective losses are thought to approach a minimum when the air velocity at the surface is (0.3m/s).

In summary, it is preferable to maintain stable environmental conditions, although there may be different optimum conditions for a specific application, (ie. vascular patterns are said to be enhanced at ambient temperatures below 25°C, Challoner (1978)).

The thermographic systems convert the detected IRE into a grey scale image, with a range which is variable, in steps from 1 to 20 degrees. In practice, the most commonly used sensitivity settings, are 1C°/division and 0.5C°/division, to provide a continuous representation of the complete field of view. At a sensitivity of 0.2C°/ division, (a range of 2C°), only small surfaces of skin can be detected simultaneously. For this reason, thermograph images cannot be used to monitor large surface area with high temperature resolution.

With the AGA 680 Model, peak temperatures are measured with the use of a manually adjusted isotherm highlighter. However, this technique depends upon the subjective criteria used by the observer, in judging the level of local highlighting adequate to identify the temperature. Although this technique has been used, Aberg and Svedmyr (1971), extremely small standard deviations were reported on the mean peak temperature, (±0.2C° - ±0.5C°) based on small sample sizes of 7 and 10. This level of accuracy would seem improbable, given the limitations of the instrumentation.

Area measurements from colour thermographs also pose difficulties, because of the fuzziness of the borders on colour isotherms. These images, magnified, show a gradual transition from one isotherm (colour) to the next. There is considerable skill required to make effective use of thermography. Simple operation of the system will provide thermographs but one must be aware of the above factors to properly interpret the information. In addition, tight control of the examination procedures is necessary to obtain reproducable results.

3.3.2 Thermograph Interpretation (Surface Considerations)

The thermograph provides primarily visual images of IRE. These data can only be transformed into information useful to clinicians, when the isotherm patterns are understood in the context of skin physiology and pathology; however, it is also necessary to be aware of the physics of infrared emissions.

Hardy and Muschenheim (1934) proposed that human skin behaved as a black body between the wavelengths of (3-15 micrometer). Borg and Mallner (1973) presented arguments, estimating the sensitivity of the detected infrared emission signal to changes in surface emissivity (ε). They observed that a 1% change in ε results in an 11% change in apparent skin temperature (approximately 0.33C° for a body at 300°K). However, as the emissivity changes, so does the reflectance (ρ).

$$\rho = 1 - \varepsilon$$

The net result is that, for a 1% change in ε, (assuming the temperature of the object is less than 15°C greater than the environment), the actual change in apparent surface temperature is only 0.15C°.

Steketee (1976) reports on the influence of various topical agents in changing the apparent temperature of a base material. Many paraplegic patients who have dry skin may use a surface barrier cream, such as "Nivea" or petroleum gel, with corresponding apparent temperature shifts of 0.2°K and 0.1°K respectively. These changes are less than the resolution of most clinical thermograms.

Young (1970) reports on Chapman's (1969) assertion that wrinkling, oedema and crusting will change the skin's emissivity (psoriasis was said to have increased the apparent temperature), although there were no objective data, or detailed discussion of these points.

The available objective data suggest that normally encountered emissivity changes in skin do not present a major problem in determining surface temperature, except where the surface of the skin is covered in fluid, (such as serous exudate from a wound), or where heavy applications of creams or ointments simulate this condition.

3.3.3 Systemic Internal Considerations in Thermographic Interpretation

In this section, the internal considerations are presented as a background to the clinical interpretation of surface emission patterns. The thermodynamics of the human body underlying surface temperatures has been described by heat flux models, based on physiological and anatomical characteristics, Branemark and Nilsson (1969); and more theoretical biotherm mathematical models.

Studies of heat flux mechanisms in tissues have produced theories on the function of physiological mechanisms and anatomical structures in this thermodynamic process. Biotherm models, Chato et

al. (1970), Mahanty (1980), and Bosiger and Scaroni (1982), have been developed to study specific problems, (there are always so many assumptions required in the modelling of biological systems, that the tool of mathematical modelling is most effective when directed towards specific questions).

The physiologic and anatomic descriptions of heat flux mechanisms are useful in appreciating the range of sources which can produce gradients in IRE on the skin's surface. Wallace and Cade (1974) report on the findings of Cooper et al.(1959), who hypothesized that heat transfer to the skin from deep sources is by vascular convection, and from superficial sources, by conduction.

Branemark and Nilsson (1969) proposed the following homeostatic equation to account for vascular connections at various tissue depths:

$$H_C + H_I = H_R + H_F + H_E$$

Sources of heat flux

H_C = blood + tissue metabolism

H_I = incident radiant energy

H_R = emitted radiant energy

H_F = conduction + convection

H_E = evaporation

Those factors affecting this balance will produce changes in the apparent surface temperature. Those influences by internal body parameters are related to the H_C. In further experiments conducted with implanted heat sources, Nilsson reported that superficial "hot spots" rarely are the result of localized increases in metabolic activity but rather the result of vascular reaction. Although there was a linear relationship between the power output of the implanted source and the surface temperature, high power outputs were required to generate significant changes in skin temperature. Saxena and Arya (1981) modelled the thermal characteristics of tissue near the skin using a variational finite element method and also noted sharp temperature variations near the surface. They hypothesized a reduction in temperature due to the lack of blood circulation and metabolic activity near the surface. This also supports the contention that deeper sources of increased heat production would be diffused at the surface.

Internal heat flux changes can be discussed in terms of metabolic influences and blood flow changes. The paraplegic subject will have little or no gluteal muscle function (except for brace ambulating patients with Spina Bifida). Consequently, their voluntary muscle activity will be concentrated in the upper body. For this reason, increases in IRE, due to superficial or deep increased metabolic activity will, in all probability, be related to tissue pathology.

Local blood flow may be influenced by neurological mechanisms in response to thermoregulation, trauma and/or systemic chemical influences. It has been observed in the OCCC tissue trauma programme that most spinal cord patients are taking a variety of

drugs to control problems such as spasticity and urological infections. There have been no studies reported which deal with the influence of such medications on temperature regulation and/ or skin temperature. In light of this lack of knowledge, it must be assumed that any effects would be systemic, and that focal points of increased IRE would not be drug induced artifacts. There is a possibility that these systemic influences might induce changes in the rate of response to various external stresses, interfering with measurements of dynamic responses.

Skin reactions to foreign materials (contact dermatitis) might stimulate local blood flow Raskin and Zies (1977) and produce IRE changes similar to those found after tissue exposure to ischaemic trauma. This type of reaction might well be identified by associated visible symptoms, which would become evident within 48 hours of contact.

There has been recent investigation of voluntary influence over skin temperature (biofeedback). The effects of such training have been primarily demonstrated on the extremities, (hands and feet) and on the forehead and temple, Mandel, (personal communication). In these circumstances, considerable training is required to overcome the autonomic control system and, as such, was assumed not to represent a source of interpretive error over the buttocks.

3.4 REVIEW SUMMARY

The main points of discussion presented in this chapter are reviewed to emphasize the progression of findings which led to the research undertaken in this programme.

1) The process of tissue breakdown, associated with the development of pressure sores, has been described by the

inflammatory model proposed by Brand and Bergtholdt (1971). This is based on the premise of repeated low levels of stress, producing periodic ischaemic conditions beyond the tolerance level of the tissue on a cumulative basis. In these circumstances, the tissue becomes chronically inflamed, and more susceptible to subsequent sudden breakdown.

2) The state of health of skin can be ascertained roughly by its colour and temperature. Warmth is associated with blood flow (dilation of arterioles), pinkness with capillary dilation, and redness or blueness, with the level of oxygenation of the blood.

3) Inflammatory and hyperaemic responses are distinguished by a rise in temperature after release from ischaemic conditions. An inflammatory response is characterized by a sustained hyperthermic response; whereas, a hyperaemic reaction cools after an initial increase in temperature.

4) The specific relationship between skin temperature rise after pressure release, and the duration and magnitude of the applied load, is presently being studied. Previous tests with mechanical probes have indicated that there is a correlation. The mathematical nature of this correlation has not been determined.

5) These hyperthermic flares have been used clinically to identify points of high risk and to assist in the modification of footwear, Bergtholdt and Brand (1975).

6) Thermography appears to be the best tool for evaluating wheelchair seating, facilitating, as it does, the locating of high risk points over a large surface. The examination exposes the subject to no risk, and the result directly assists in the design process.

7) The colour thermograph provides a real-time image highlighting isotherm patterns at resolutions of up to 0.5C° per division. Although the instrumentation can be set at sensitivities of 0.1C°, the field of view is too small to be practical.

8) Isotherm borders are difficult to define accurately when transcribed directly from the video image. Consequently, such measurements should be made by automated techniques.

9) Topical agents have been shown to shift the apparent surface temperature on a test substrate up to 0.7C°. However, for clean dry skin the expected apparent skin temperature shift should be less than 0.25 C°.

10) There is no information available on the systemic or local skin temperature changes induced by drugs. Paraplegic patients often have a combination of several medications which would complicate detailed studies of these possible effects. It must be assumed that any resulting anomalies will be systemic rather than localised. Nevertheless, the patients medication should be documented.

11) Local reactions to topical agents, such as antigens, need to be considered as a source of artifact, with respect to pressure studies, but their discovery may prove useful to the patient who might otherwise be adversely affected by such reactions.

CHAPTER 4 PRELIMINARY PATIENT STUDIES

4.0 INTRODUCTION

This chapter presents a preliminary analysis of thermographs obtained during patient studies. The objectives of this analysis are to determine: 1) if there is adequate information available from microfiche skin tone and thermographic records to augment a tissue trauma programme; and 2) which measurements ought to be studied by automated digital techniques.

Photographic records were used to classify skin condition and type. These data were compared with corresponding thermographs recorded after 15 minutes of cooling in ambient conditions. Temperature ranges were estimated, corresponding to the following clinical options for management; a) complete bedrest, b) reduced sitting time, c) maintenance of existing sitting duration, or d) increased sitting times. Automatic analysis was considered necessary to further characterize the cooling rates during the first fifteen minutes of cooling.

4.1 METHOD

4.1.1 Examination Protocol

This study comprises a review of patient data collected over a 3 year period. The following types of studies are included:

4.1.1.1 Screening Examinations

Those patients returning for review, or being seen only on an infrequent basis, were thermographed after sitting for a known period of time. The actual time for each patient varied in accordance with factors such as personal routines, time required for travelling to OCCC, etc.

4.1.1.2 Serial Studies

These consisted of a clinically defined series of examinations which took place during that period of time when a seating system was being evaluated. To establish a baseline, the initial thermographic examination was preceded by a period of weight relief, ie. no sitting for a minimum of 12 hours prior to the examination. This, and a clinical evaluation by the physician, provided the guidelines for establishing optimum or maximum sitting times for each patient within the estimated limits of his/her tissue tolerance. These tests were repeated as frequently as deemed necessary by the physician and/or author during the process of seating evaluation. A rapid series of daily tests was feasible for in-patients, but difficult for out-patients who frequently required several days notice to arrange transportation.

4.1.2 Population

This study has been compiled from the files of 80 subjects and includes data from 161 examinations. The subjects were OCCC patients referred from Spina Bifida review clinics and adult spinal cord injured patients, referred from other treatment centres within Toronto. Seventy-five percent of the patients had a history of chronic pressure sores, and only 20% were considered low risk.

4.1.3 Detailed Procedure

Examination techniques were developed over several years. The thermographs recorded surface temperature changes in the buttock

tissues after relief of sitting pressure. The detailed procedure is described in Table 4.1.

The maximum temperature data for analysis in this chapter were obtained from the thermographs recorded after the subject cooled in fixed ambient conditions for fifteen minutes. The higher resolution thermograph, (sensitivity-0.5C°/div) was used when the maximum temperatures were less than 35.5 °C. These temperature data were combined with the tissue type and condition gradings for comparative analysis, see Table 4.2.

4.1.4 Documentation and Retrieval of Data

Because most of the data in this programme are visual, a novel storage and retrieval system was devised to facilitate their management. The thermographs and visual pictures of the skin were stored on microfiche, for ease of retrieval and comparison (Figure 4.1).

An element of subjectivity was inevitability introduced in the effort to describe the level of "Tissue Quality" from photographic records. For the purposes of this dissertation "Tissue Type" designated the visible irreversible pathological changes in tissue structure. "Tissue Condition" was graded according to the surface discolouration corresponding to stages of acute response to trauma. Such data were obtained for each area of skin overlying the five bony prominences, left and right ischial tuberosities (ITL & ITR), left and right greater trochanters (GTL & GTR), and sacrum (S), Figure 4.2.

Colour grading of photographic material has been described as an unreliable technique for assessing skin blood flow, and hence,

TABLE 4.1 CLINICAL EXAMINATION PROTOCOL

1	camera Warm-up (30 minutes)
2	calibration with absolute temperature reference
3	frontal and side view photographs of patient in wheelchair
4	completion of a history sheet recording personal data such as: a) daily sitting habits (duration of time in/out of chair) b) duration of immediate sitting time c) activity prior to examination d) description of seating systems e) current skin status and recent incidence of sores
5	start of timer
6	transfer to examination plinth which has an elevating surface under the subject's trunk supporting the subject in the genupectoral position
7	preparation of patient (exposure of skin and locking knee support)
8	positioning and focusing of camera
9	a) clinically oriented examinations: view - full field of buttocks and upper third of posterior thigh sensitivity - 1C°/division and 0.5C°/division thermographs - 110 mm (<2, 5, 10 and 15 min after timer start) photographs - 110mm (2, 16min) foil markers to locate anatomical sites in the thermograph applied 2-5 min after timer start

TABLE 4.2 DATA FORMAT

CODE	1	2	3	4	5	6	7	8
DATA	7	. 05	7	. 030	1	. 12	32	. 5

Code description:

1. subject identification code.
2. examination number
3. seat classification code
4. sitting time (min)
5. tissue site (see figure 4.2)
6. tissue type-condition (see section 4.1.5).
7. & c. skin temperature (C°)

The following seating systems were included in the analysis (coded as indicated below).

Code	Cushion Description	Wheelchair Base
00	none	hammocked canvas
01	polyurethane foam (PF)	" "
02	" "	plywood
03	temper foam (T41) +1"(PF)	plywood
04	contoured (T-41), P.F.)	plywood
05	" (T-51, P.F)	plywood
06	Roho (air)	hammocked canvas
07	" "	plywood
08	Bye-Bye Decubiti (air)	hammocked canvas
09	" " " "	plywood
10	type 05 +(expanded poly-styrene beads)	plywood
11	Reston (Gel)	hammocked canvas
12	Reston (Gel)	plywood
13	Rubber Ring (air)	plywood

FIGURE 4.1 MICROFICHE FILE

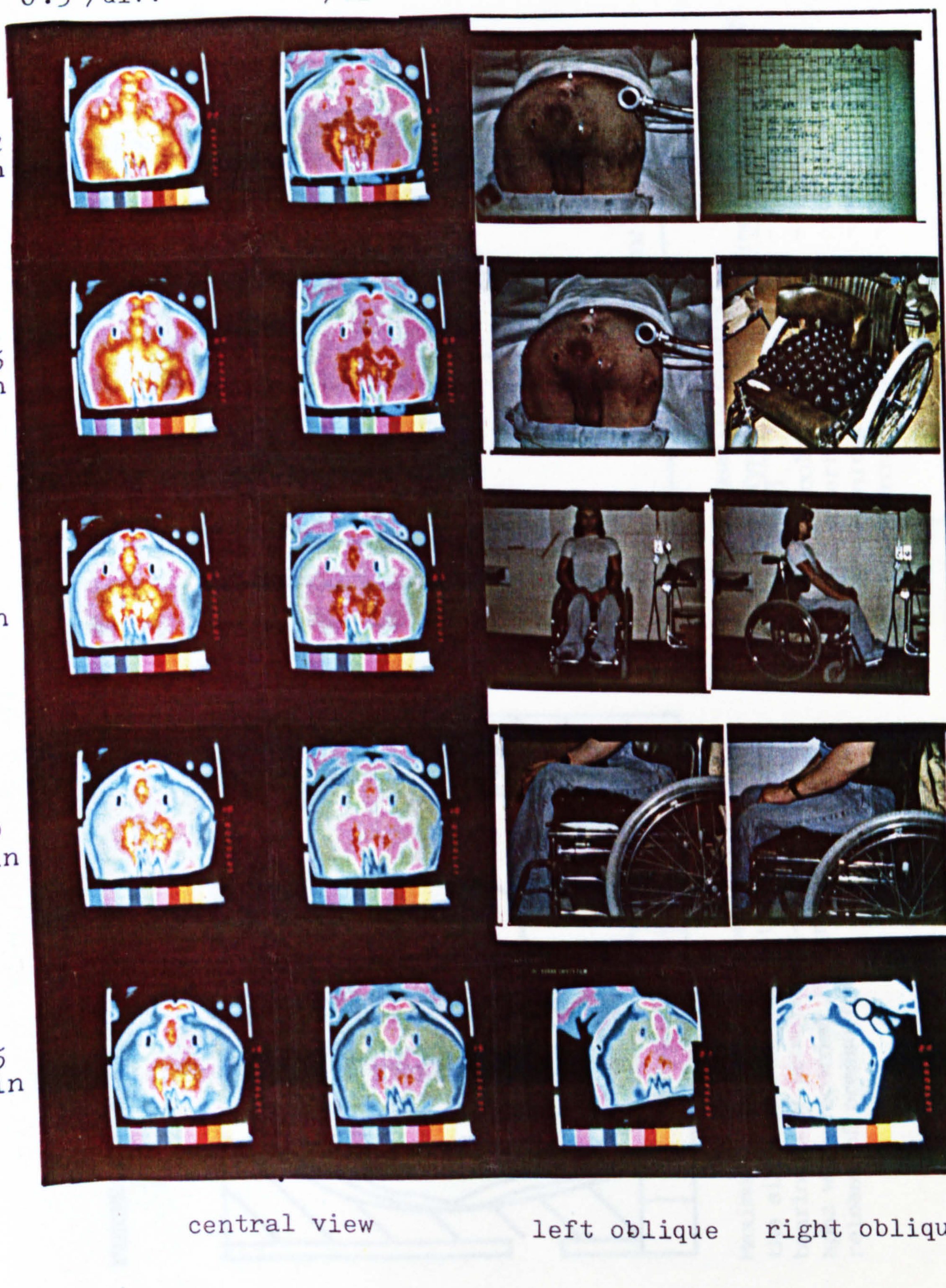
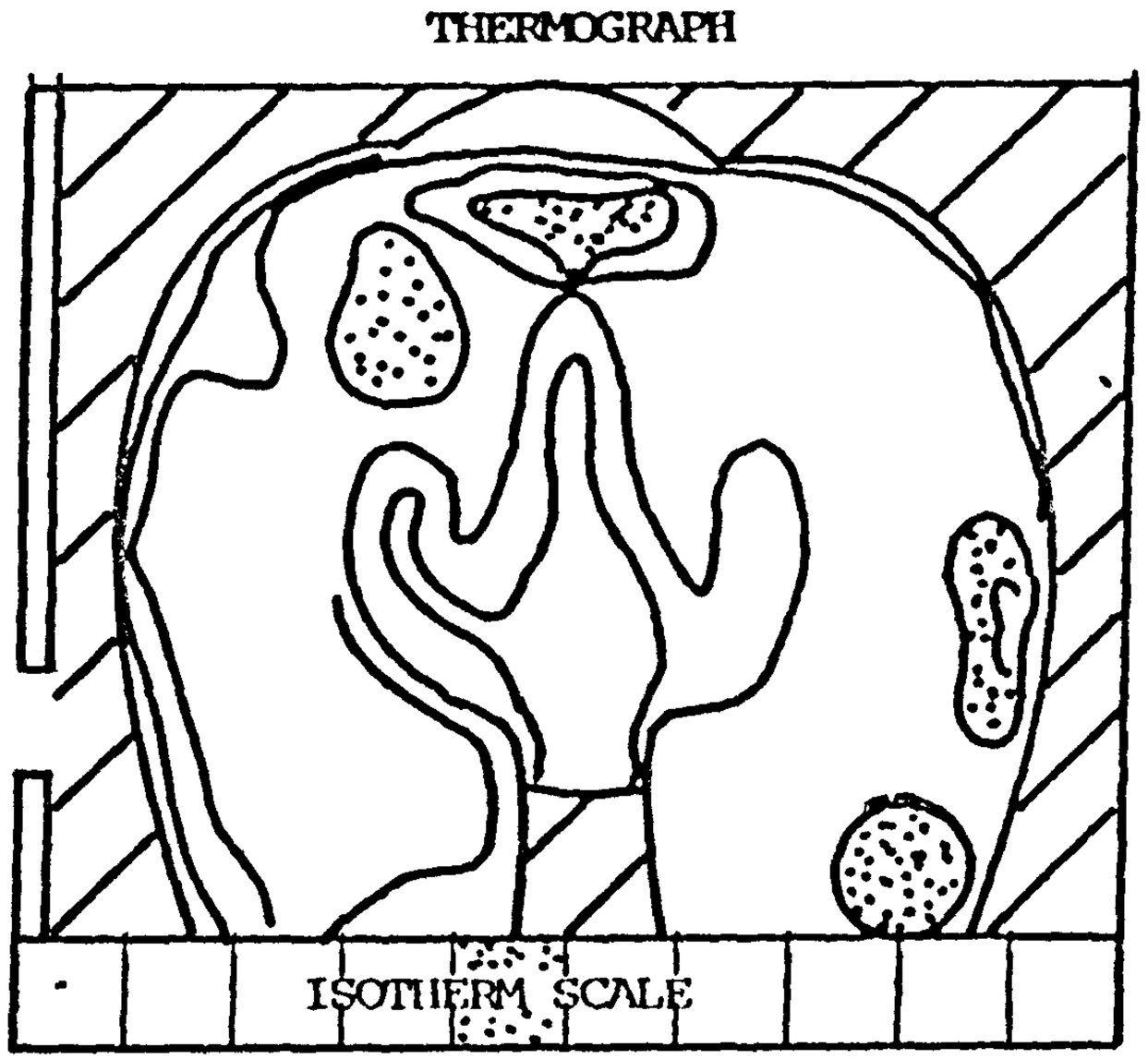
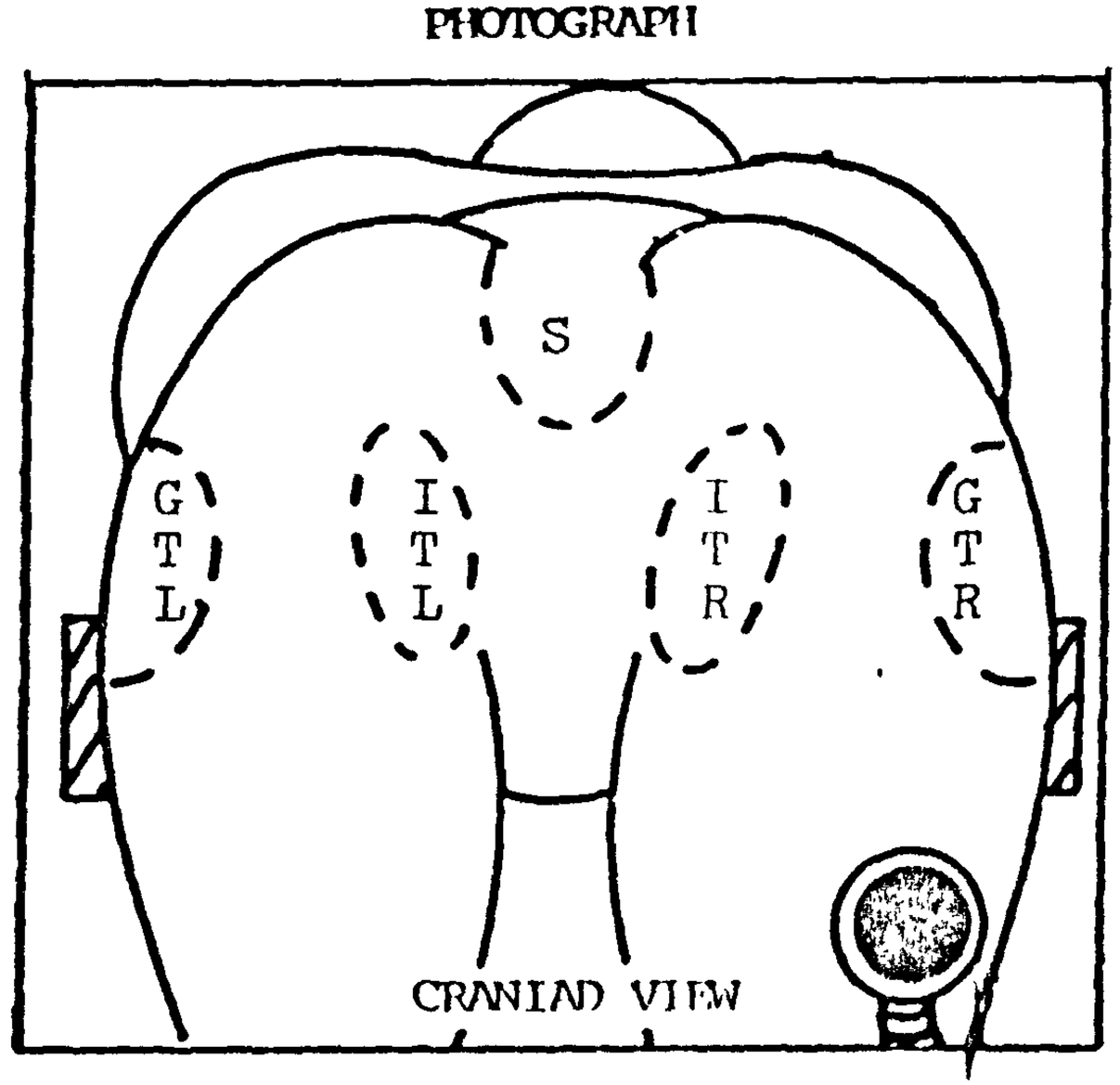


FIGURE 4.2 DATA SOURCES FOR LOCALIZED MAXIMUM SKIN TEMPERATURE





Maximum temperatures were recorded from the sites corresponding to the weight-bearing bony prominences. The thermographs were recorded 15 minutes after release of pressure.

Tissue Quality Grading:

Tissue Type (TT)	Tissue Quality (TC)
1 - good	1 - clear
2 - discoloured	2 - hyperemic
3 - superficial scars	3 - inflamed
4 - surgical scars	4 - surface lesion
5 - neurovascular flap	5 - deep lesion, bursa

tissue viability, Adamson (1978). The relationship between these types of data and maximum temperature data is explored in this chapter.

4.1.5 Assessment of Tissue Quality

A range of cases is presented in Figures 4.3, 4.4 and 4.5 to demonstrate the classification system, and to illustrate the range of pathology included in the analysis.

4.1.5.1 Tissue Types

GOOD (1): There is no visible evidence of scar tissue or localized discolouration.

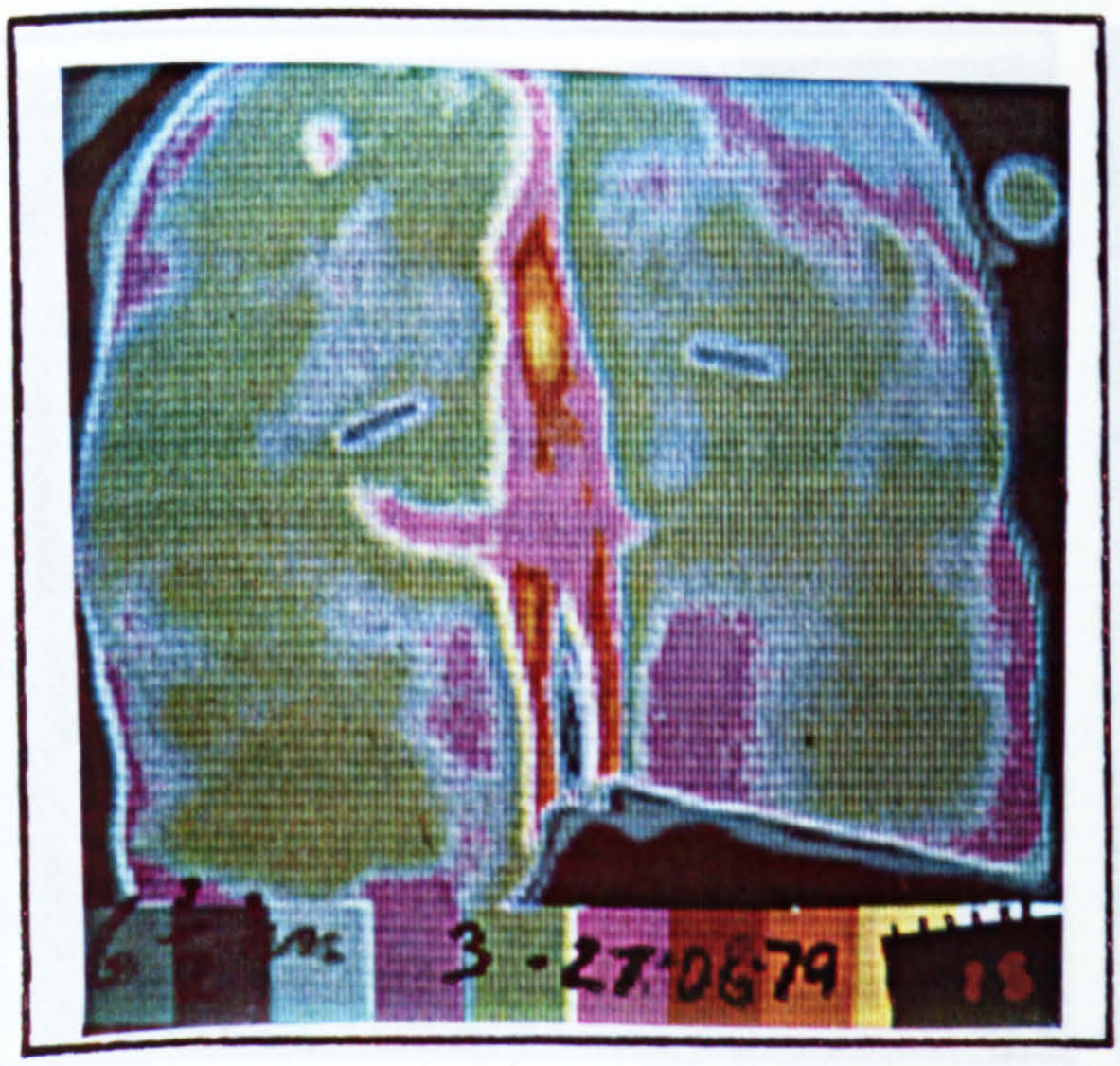
DISCOLOURED (2): The appearance of a localised change of skin colour, over any of the bony prominences, which persists throughout the examination. This can be difficult to distinguish from hyperaemic redness or inflammation which tends to be pinker in hue. A brown red hue which resolved over successive examinations was associated with the healing process from previous trauma.

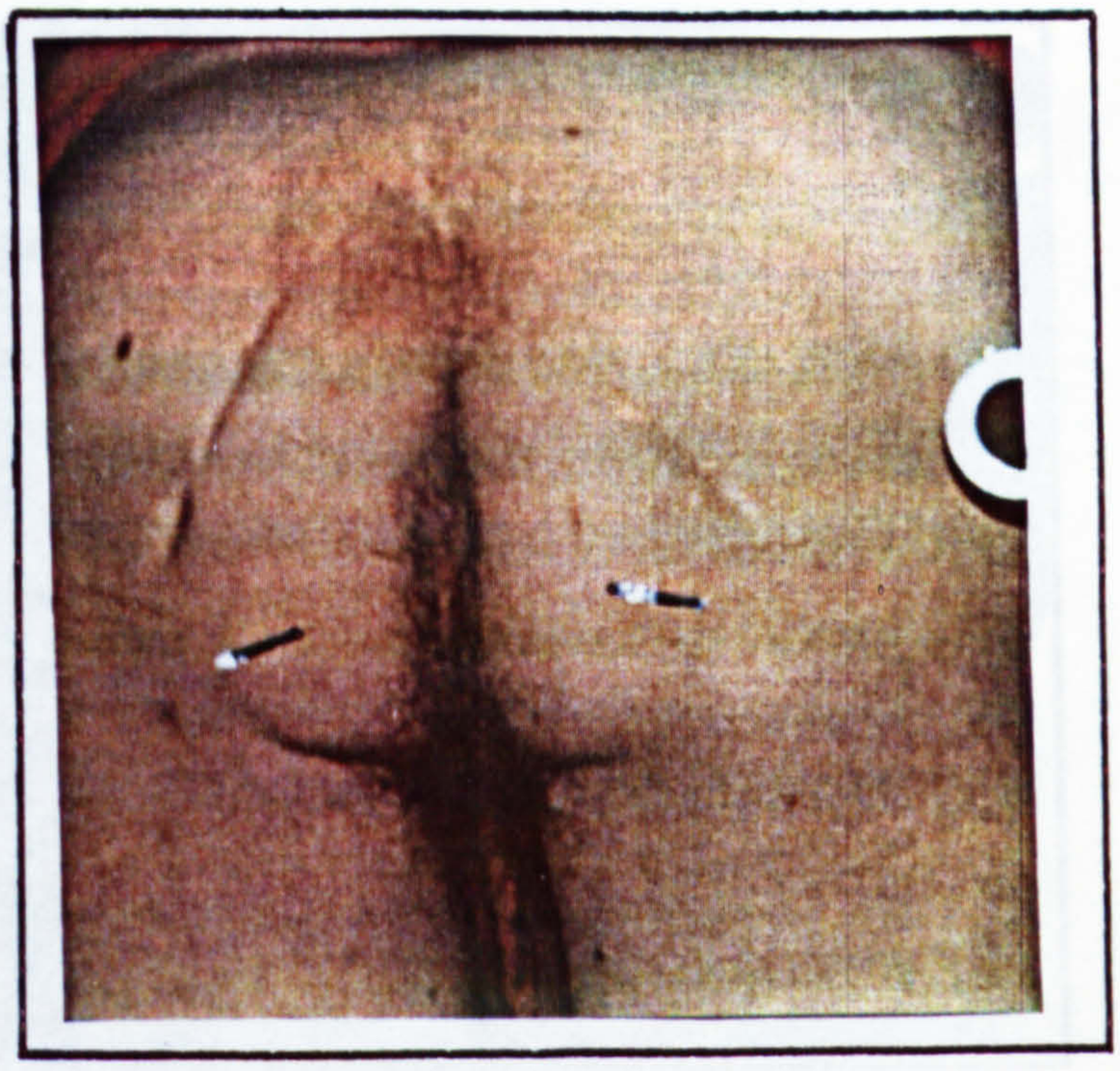
SCARRED (3): This category refers to small round scars which are the result of the healing of small pressure sores.

SURGICAL REPAIR (4): Post-surgical sites, such as those produced by a Limberg-flap procedure, were identified by the presence of characteristic geometrical surgical scars. Other flaps and graft procedures were also noted to leave specific scar patterns.

NEURO-VASCULAR FLAPS (5): Only three patients on the OCCC caseload had had this procedure during the past five years. Two were included in this study group.

FIGURE 4.3 TISSUE QUALITY AND MAXIMUM SKIN TEMPERATURE OBSERVATIONS
(HEALED TISSUE - PROLONGED STRESS)

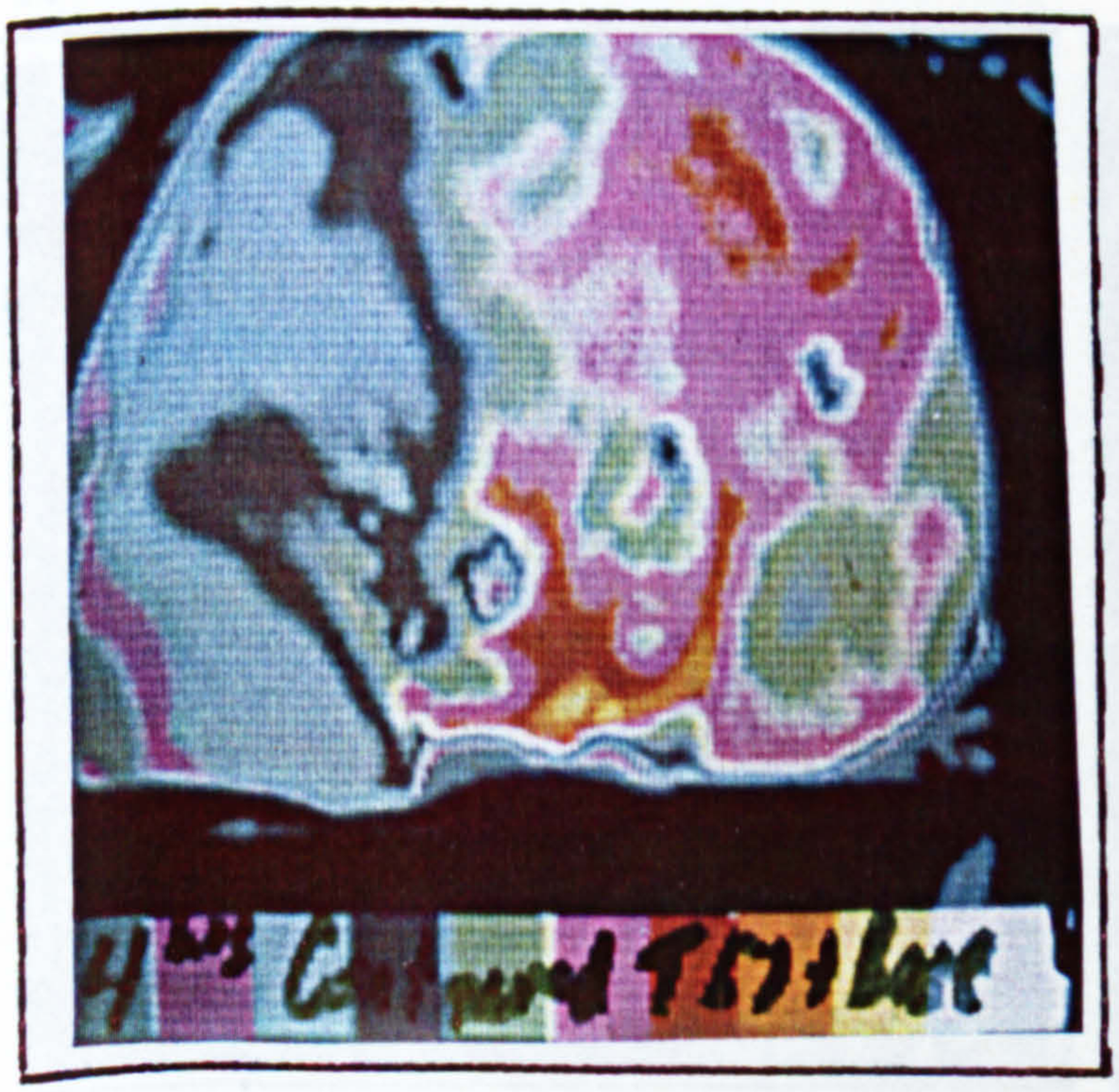


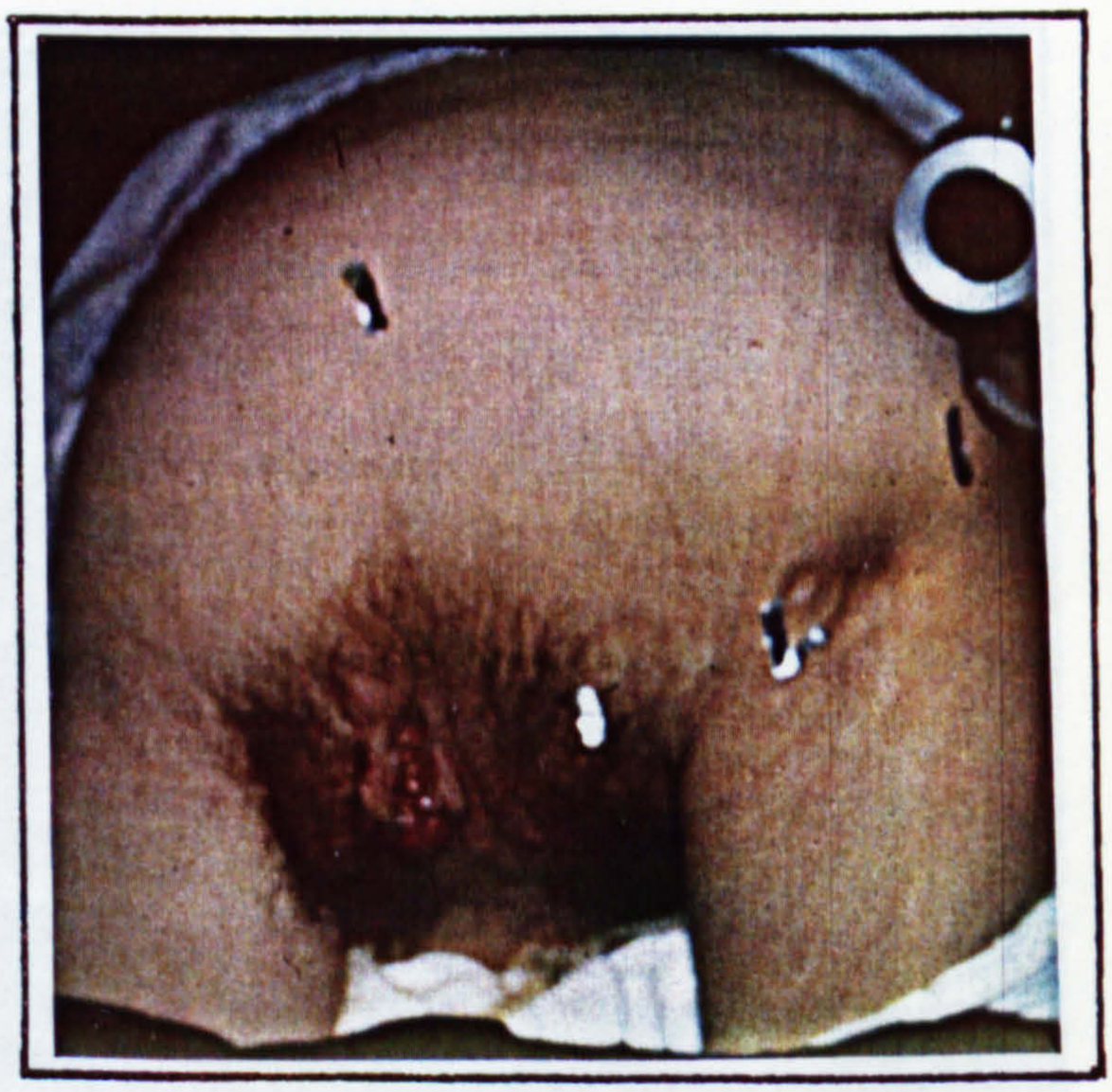


CASE (TB)

6.5 HR. Roho;
safe for prolonged
sitting

TISSUE TYPE	1	3	3	1	1
TISSUE CONDITION	1	1	1	1	1
PEAK TEMPERATURE (°C)	32.5	34.0	34.0	33.0	32.5
TISSUE SITES	LGT	LIT	S	RIT	RGT



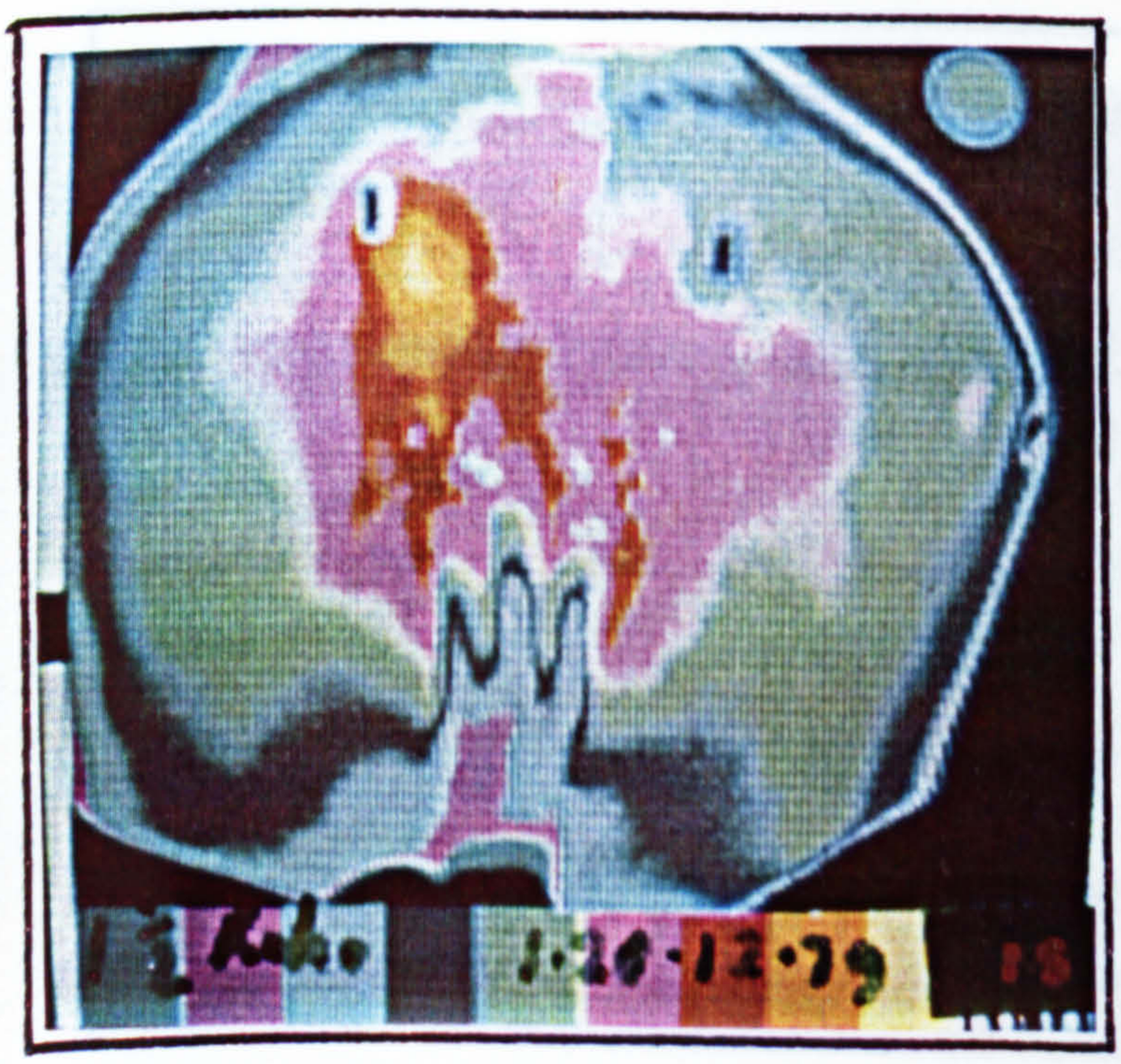


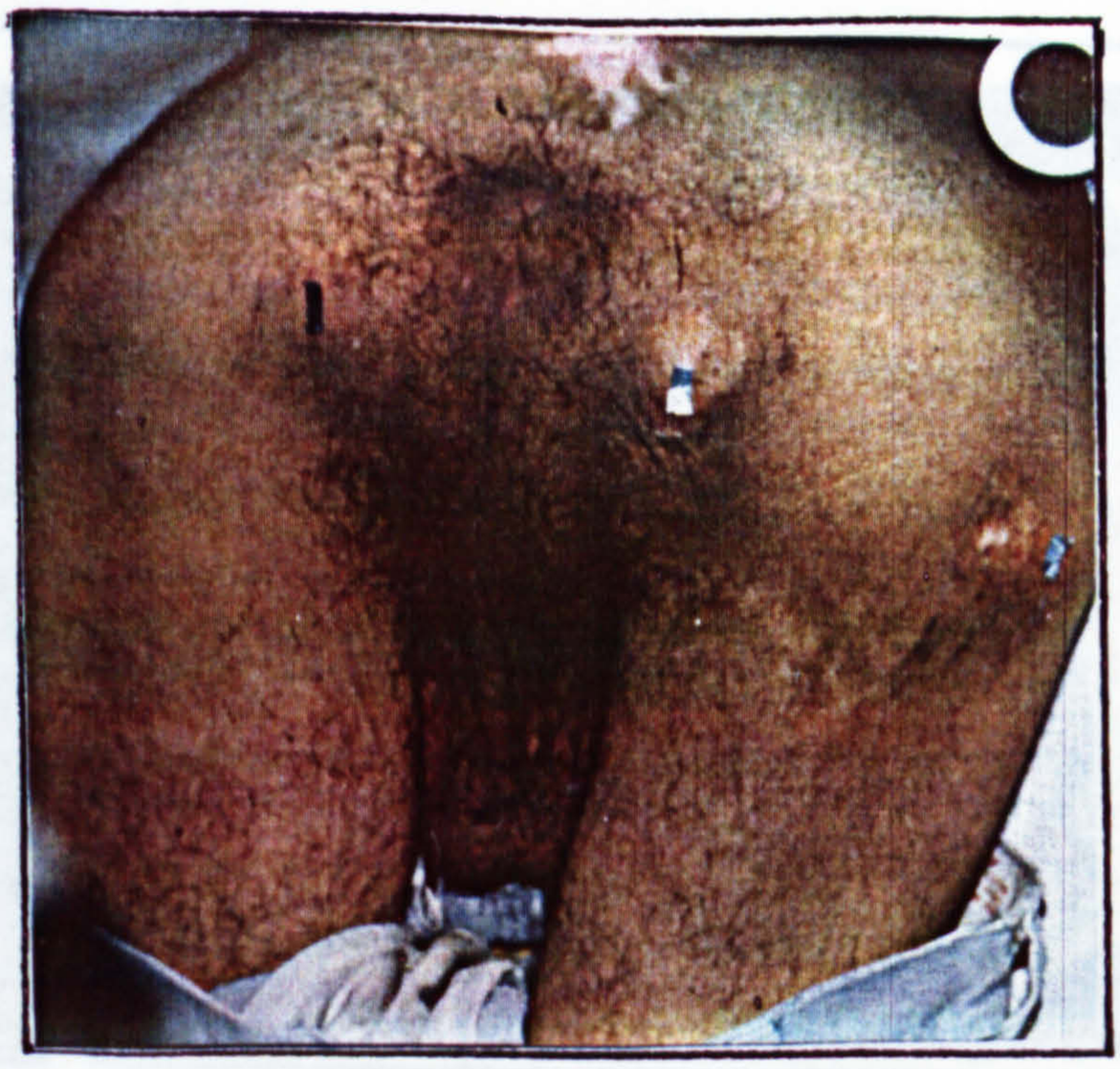
CASE (HR)

4 HR. contoured
soft foam plus
warning system;
safe at present
sitting levels

TISSUE TYPE	1	1	1	2	3
TISSUE CONDITION	1	1	1	2	2
PEAK TEMPERATURE (°C)	-	32.0	34.0	35.0	35.0
TISSUE SITES	LGT	LIT	S	RIT	RGT

FIGURE 4.4 TISSUE QUALITY AND MAXIMUM SKIN TEMPERATURE OBSERVATIONS
(ACUTE INFLAMMATION - SHORT STRESS DURATION)

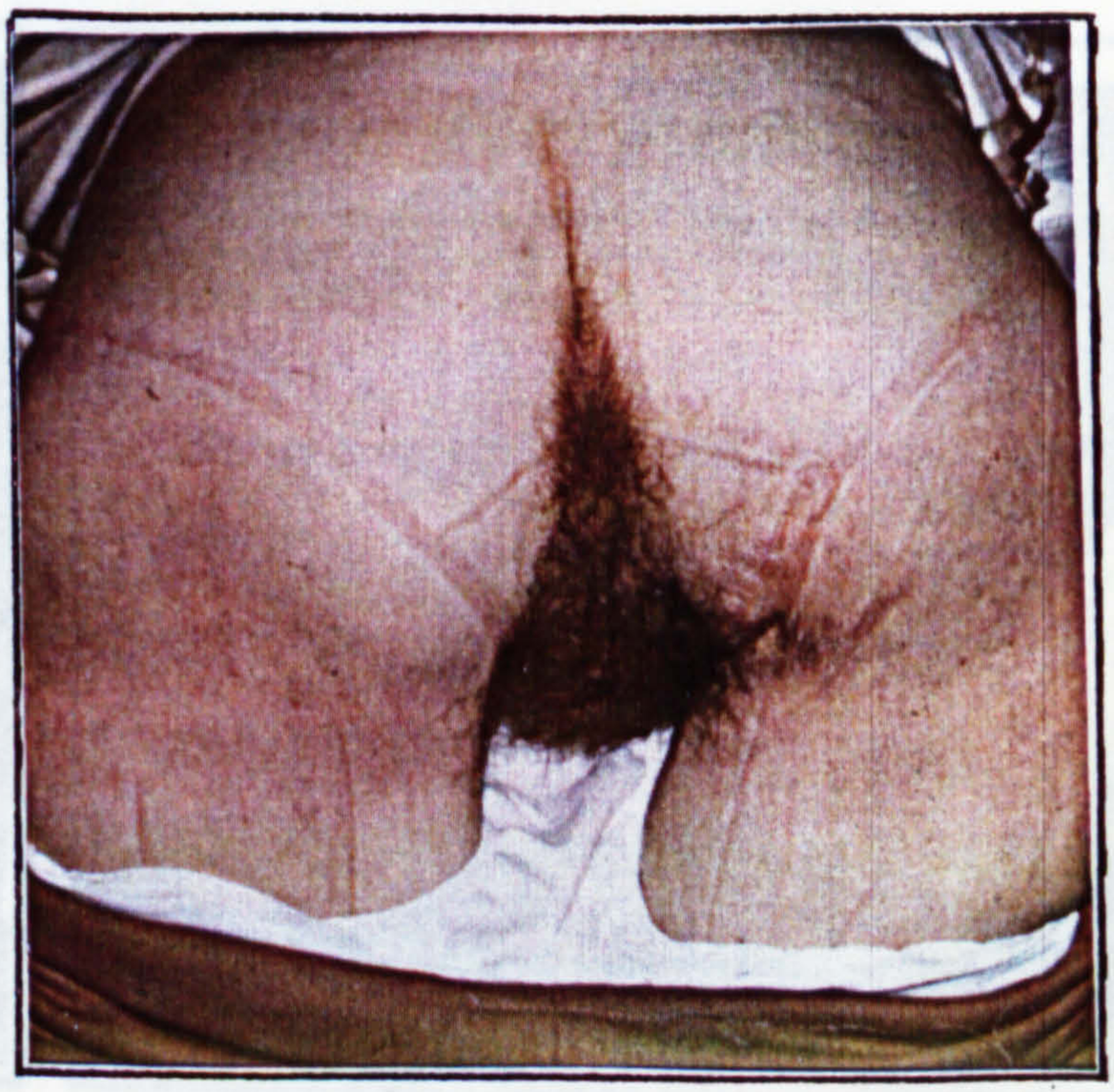




CASE (CD-3)

1.5 HR. Roho;
LIT appears to be
Inflammed;
stop sitting and
check baseline for
restart on sitting programme

TISSUE TYPE / TISSUE CONDITION	PEAK TEMPERATURE (°C)	TISSUE SITES
1 / 1	33.0	LGT
2 / 3	37.0	LIT
3 / 4	35.0	S
3 / 1	34.0	RIT
3 / 1	34.0	RGT

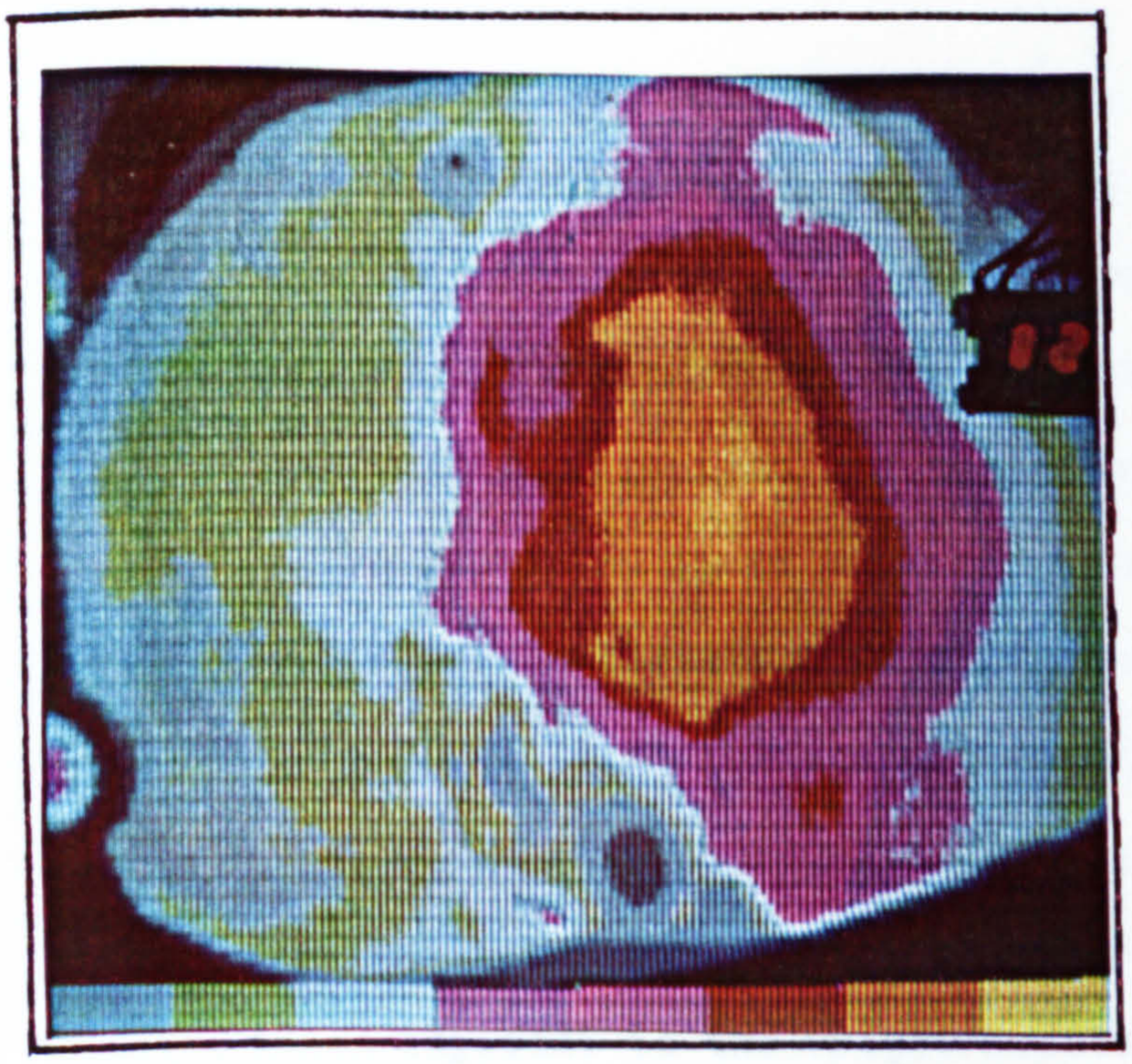


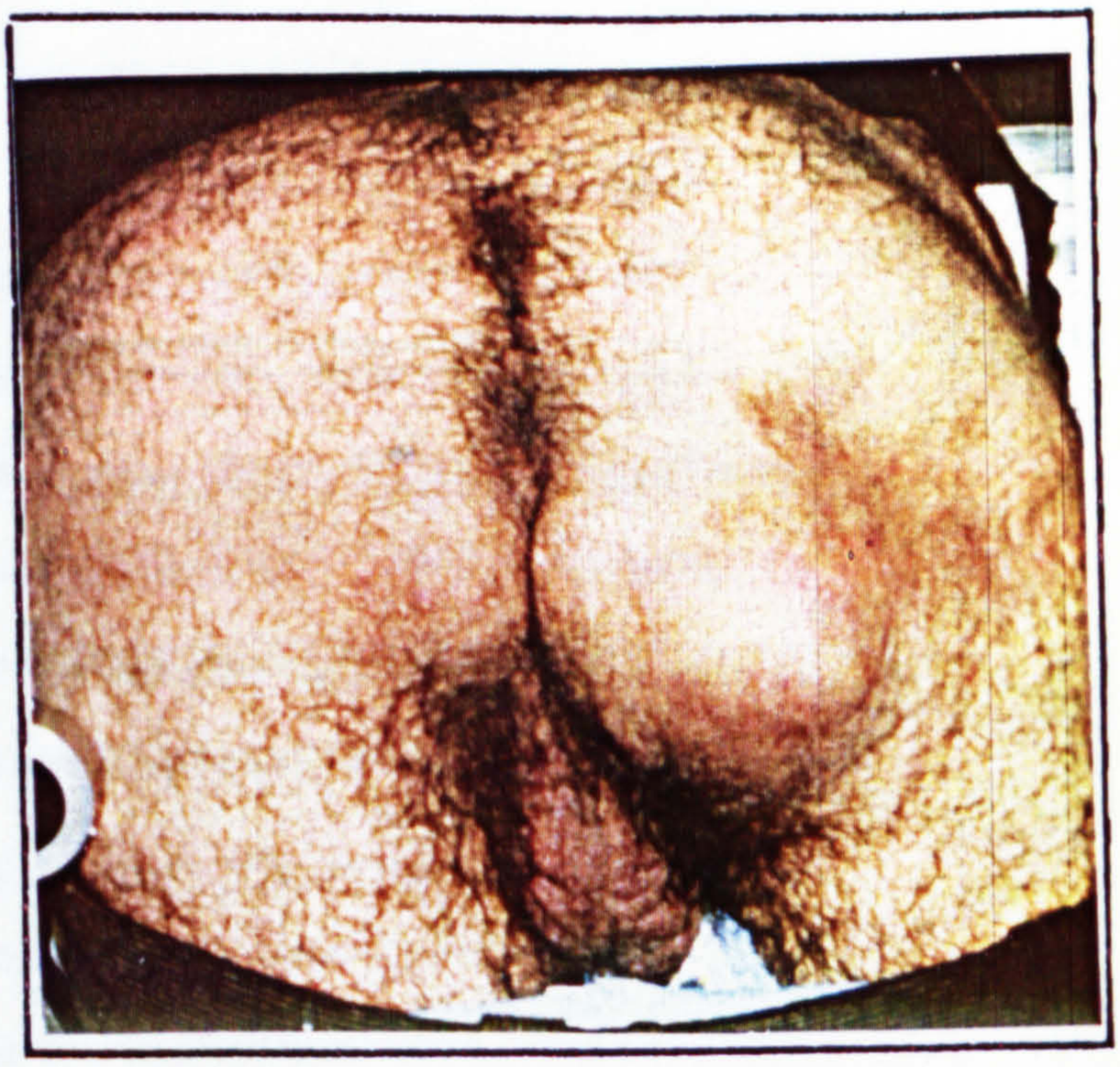
CASE (ES)

2 HR. contoured
soft foam ;
acute inflammation over
S and RIT;
clinic review

TISSUE TYPE / TISSUE CONDITION	PEAK TEMPERATURE (°C)	TISSUE SITES
1 / 1	34.0	LGT
1 / 2	34.0	LIT
1 / 1	36.0	S
4 / 2	36.0	RIT
1 / 1	35.0	RGT

FIGURE 4.5 TISSUE QUALITY AND MAXIMUM SKIN TEMPERATURE OBSERVATIONS
(CHRONIC INFLAMMATION - NO STRESS)

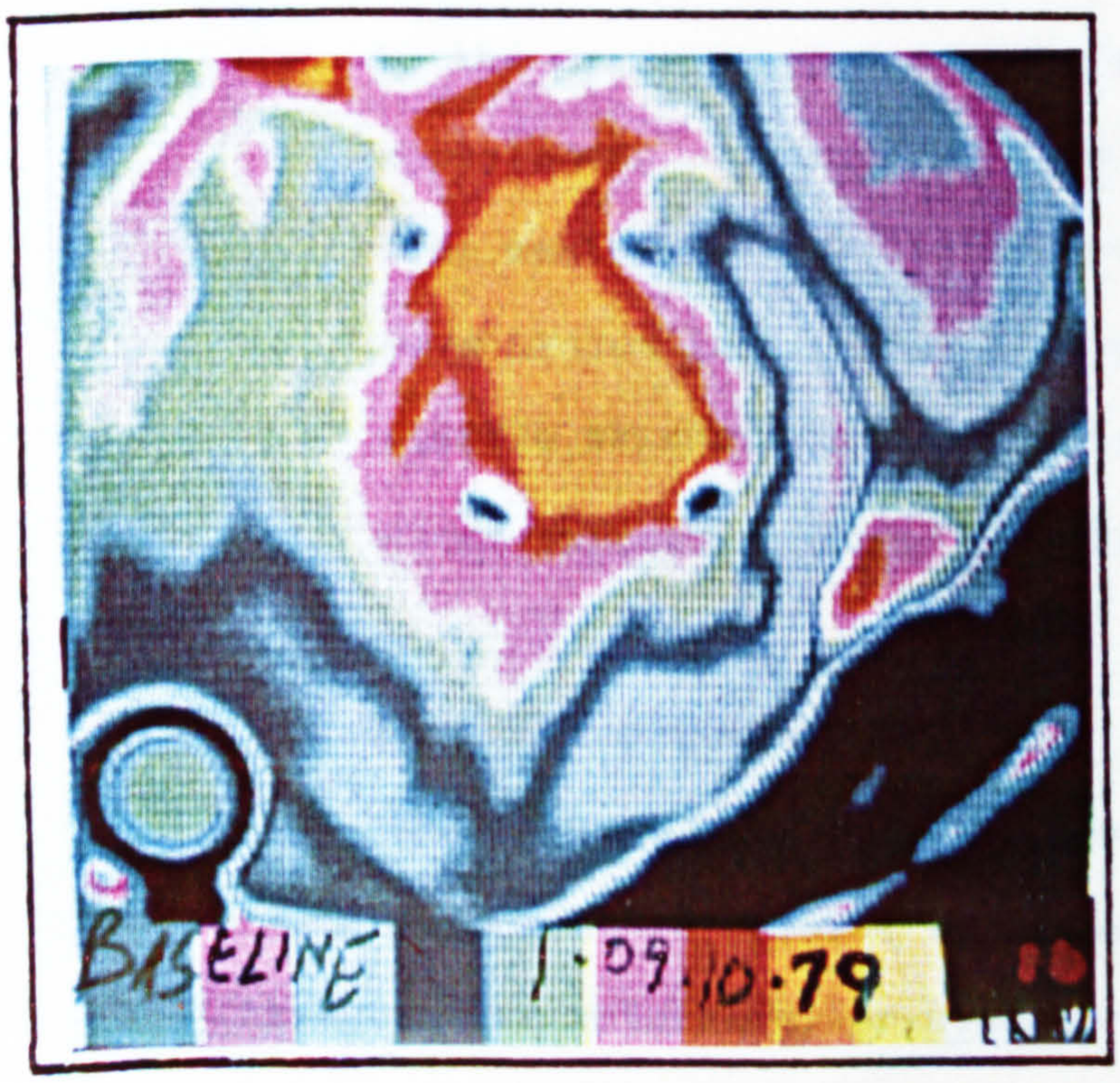


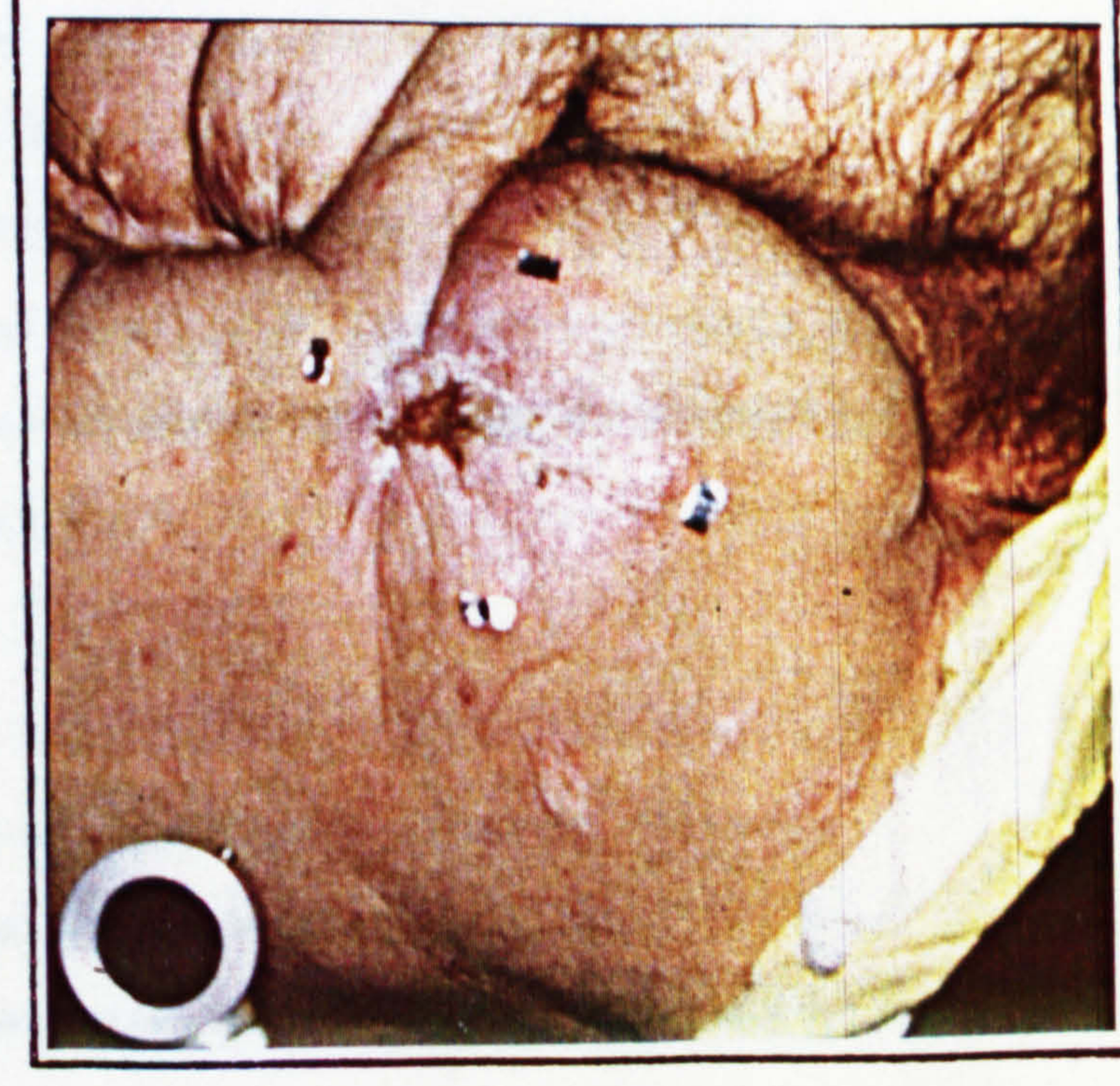


CASE (CD-1)

Baseline - no sitting; acute inflammation of subcutaneous bursa; no sitting until reduction in baseline skin temperature (2-3 weeks)

TISSUE TYPE	1	2	3	3	3
TISSUE CONDITION	1	3	4	1	1
PEAK TEMPERATURE (°C)	33.0	37.0	35.0	34.0	34.0
TISSUE SITES	LGT	LIT	S	RIT	RGT





CASE (JL)

Baseline review; low grade chronic infection of scar tissue suspected; referal to plastic surgeon

TISSUE TYPE	1	1	1	4	1
TISSUE CONDITION	1	2	1	2	1
PEAK TEMPERATURE (°C)	34.0	34.0	36.0	36.0	35.0
TISSUE SITES	LGT	LIT	S	RIT	RGT

4.1.5.2 Tissue Condition:

The accuracy of assessment of tissue condition from the microfiche records was dependent upon its visual quality and associated examination notes. Particular care was required to distinguish chronically discoloured tissue from either a hyperaemic response, or an acute superficial inflammation. The following visual characteristics were assigned to each category:

CLEAR (1): No sign of skin discoloration, as documented in the first skin photograph (usually within two minutes of pressure relief). This was best judged by comparison with tissue adjacent to the weight-bearing prominences.

HYPERAEMIC (2): This response, with fair skinned patients, was characterized by localized pinkness or flushing, which decreased in surface area during the cooling period; note 2 and 15 minute pictures.

INFLAMED (SWOLLEN) (3): Acutely inflamed tissue was identified by the presence of a deeper red discolouration, often shiny in appearance. Visible swelling was interpreted as indicating deep seated lesions in the underlying tissue.

OPEN LESION (4): These lesions were identified on the basis of visible skin disruption. Clinical notes were used to identify known sinuses or connecting tracts.

4.1.6 Thermographic Data

The thermal data used in this analysis were obtained directly from photographic records of colour thermographs. The AGA temperature reference, present in all the examinations, provided a

known absolute reference temperature for calibration. These readings were estimated to within (± 0.25°C) (one half of the smallest scale unit on the colour monitor). Because the calibration temperature had to be colour matched prior to use of the system at a scale resolution of (± 0.25°C), the total error possible was (± 0.5C)°, as illustrated in Figure 4.6.

Two other sources of error are indicated on Figure 4.6: the loss of data immediately following pressure release due to the preparation time for the subject. This included transferring the patient from wheelchair to plinth , partial disrobing, focusing of thermographic camera, and photographic set up. These preparations required from one to three minutes to complete. Because of this slow start, the analysis focussed on the information available beyond the initial few minutes of rapid cooling. Those thermal patterns emerging during the first five minutes, as a result of differing local tissue cooling rates, continued to be evident after fifteen minutes. This was found to be an acceptable exposure time for the patients, and adequate also for the collection of thermographic data.

The second source of error was the time of the photographs. The lapse time indicator was calibrated in minutes, and hence the actual time estimations were ± 0.5 min.

The thermographs were recorded on ER110 colour slide film and later projected on a microfiche reader, providing an image 26cm x 24 cm for review and measurement. The film exposures were approximately of 2 seconds duration, recording 32 frames of random interlaced image, which improved the border definition between the isotherms, thus facilitating temperature measurement.

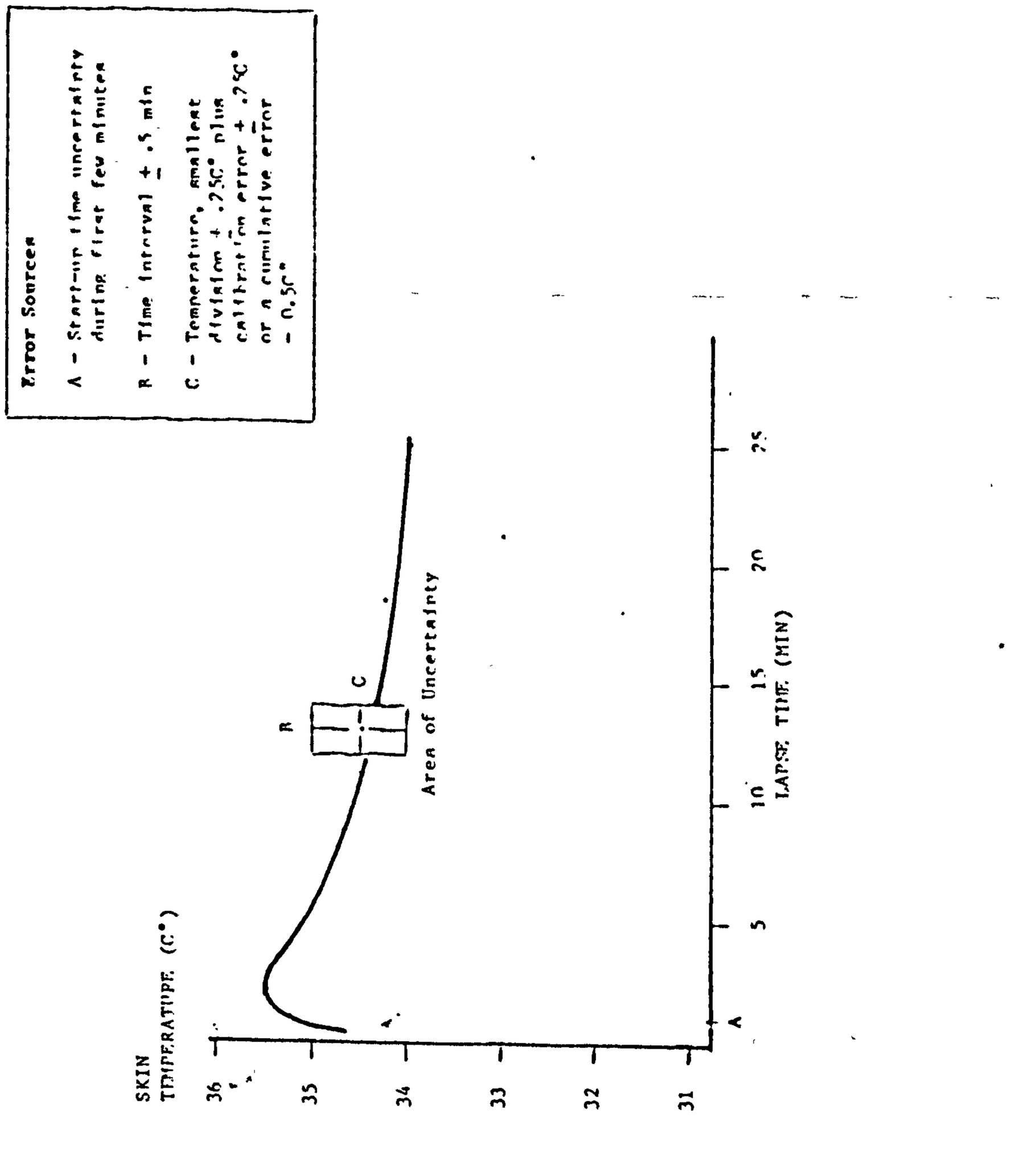


FIGURE 4.6 MAXIMUM TEMPERATURE MEASUREMENT ERROR

4.2 ANALYSIS OF MAXIMUM TEMPERATURES

4.2.1 Relative Maximum Peak Temperature Distribution

The thermographs provided information about both absolute and relative skin temperatures. The analysis was used to detect differences in relative temperatures between the weightbearing bony prominences. The datum used for these calculations were obtained from the maximum temperature at each site.

The colour thermograph displays isotherm patterns consisting of both absolute temperature and spatial data. The actual surface area of skin within the full thermographic field of view is a complex, three dimensional, curved surface, represented on the monitor by a flat projection. For this reason, absolute spatial information could only be obtained through a series of thermographs, taken at different angles, and with a visible grid in direct contact with the skin. The reconstruction of a true surface configuration would present immense difficulties in analysis, and such a reference grid would probably interfere with the thermal data. For this reason, it is not possible to refer to true thermal gradients.

The simplified approach used in this section, involved the digitization of peak skin temperature for those bony prominences known to bear most weight (greater trochanters, ischial tuberosities, and sacrum). Relative temperatures were calculated for these sites by subtracting the lowest tem perature from the rest.

This section of the peak temperature analysis deals with the identification of persistent thermal patterns and their relationship with other parameters, such as the subject's seat type, sitting time and tissue quality. The relative temperatures for the five weightbearing bony prominences were displayed, as seen in Figures

4.11 and 4.12. The Y axis represents the relative temperatures, with respect to the minimum temperature for that examination.

Example Conversion:

Subject Code . Exam Code	Seat . Time Code (Hr X 10)	Site . Tissue Type/Condition	Tmax,	Trel. (C°)
48 . 01	12 .065	1 . 42	34.0	+2
" "	" "	2 . 42	35.5	+3.5
" "	" "	3 . 41	32.0	0
" "	" "	4 . 12	36.0	+4
" "	" "	5 . 41	32.0	0

The same calculations of averages, standard deviations and correlations were used for these relative temperatures. The presence of strong trends between the relative temperatures and the other graded parameters (tissue type, condition and sitting time), would emphasize the significance of studying thermal gradients.

4.2.2 Statistical Analyses

The measurements employed in this clinical retrospective study are described in the table below:

Table 4.3 Levels of Measurement

SCALE	MEASUREMENT
NOMINAL	seat type
ORDINAL	tissue type, tissue condition
INTERVAL	
RATIO	temperature, time, subject age

The tissue gradings were considered ordinal measures as they both could be graded in terms of increased severity . The tissue type was scaled on the basis of visible evidence of specific types of scar tissue. The tissue condition was graded in accordance with the appearance of discolouration and/or swelling. This, of course, was more dependent upon the skill of the observer for consistency.

Population characteristics such as age, examination frequency and traumatic score distributions were presented in the form of frequency histograms. Bivariate frequency histograms were used to provide more detail such as the anatomical distribution of Tissue Quality gradings. Since tissue type and condition were only ordinal measures, further statistical techniques such as χ^2 test for independent samples and the contingency coefficient (C) for correlation (Siegel, 1956) were not applicable under the basic assumptions of the tests. The large number of tied values invalidated the use of such techniques as the non-parametric Spearman rank correlation analysis to determine the degree of

association between the ordinal tissue gradings and skin temperature.

Parametric statistical techniques were applied to seek correlations between the ratio measures of sitting time and skin temperature. The Pearson correlation coefficient was used to calculate the product moment correlation coefficients (r), (Ferguson 1978) the data were grouped to test the following series of constraints.

a) all samples

b) baseline examinations only (ie. sitting time = 0)

c) samples with sitting time) 0

d) sitting time) 0, cushion type = type 1, to 13 independently. Each seating system was considered as a separate constraint.

The results of these calculations are listed in Table 4.4, based on the following caclulations to determine the Pearson correlation coefficient (r)

$$r = \frac{\Sigma XY - \frac{(\Sigma X \Sigma Y)}{N}}{\left[\left[\Sigma X^2 - \frac{(\Sigma X)^2}{N}\right]\left[\Sigma Y^2 - \frac{(\Sigma Y)^2}{N}\right]\right]^{\frac{1}{2}}}$$

where X and Y represented the paired variables. These r values were then compared with the corresponding critical r values, given the number of samples, with respect to the level of significance of the correlation. In addition, the percentage of association between variables was calculated, based on the r^2 values.

$$\% \text{ assoc.} = 100\ r^2$$

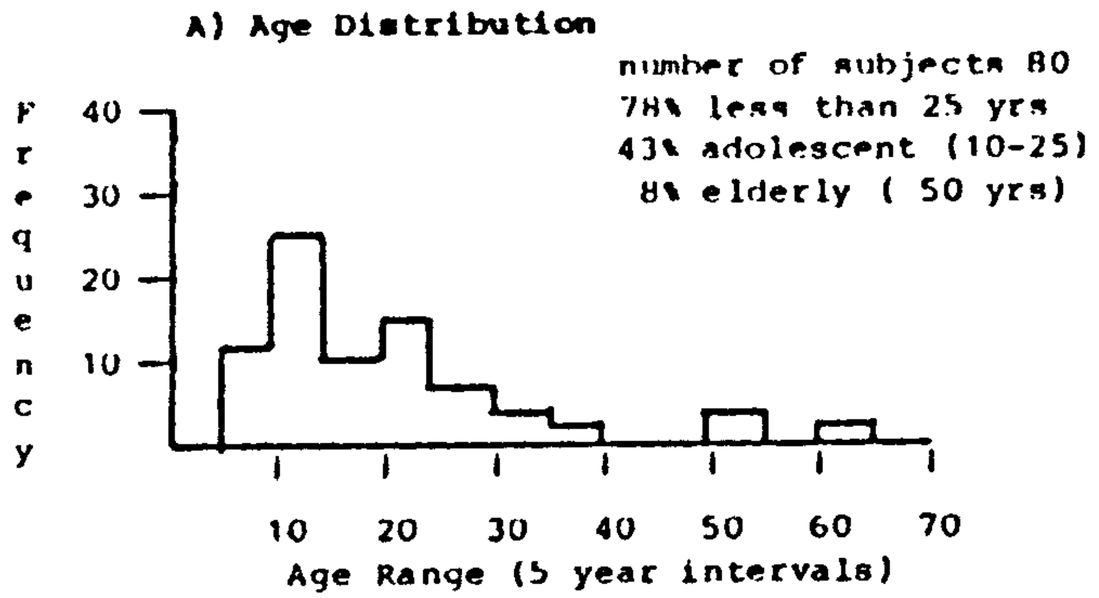
This describes the percentage of variation in one variable determined by a second.

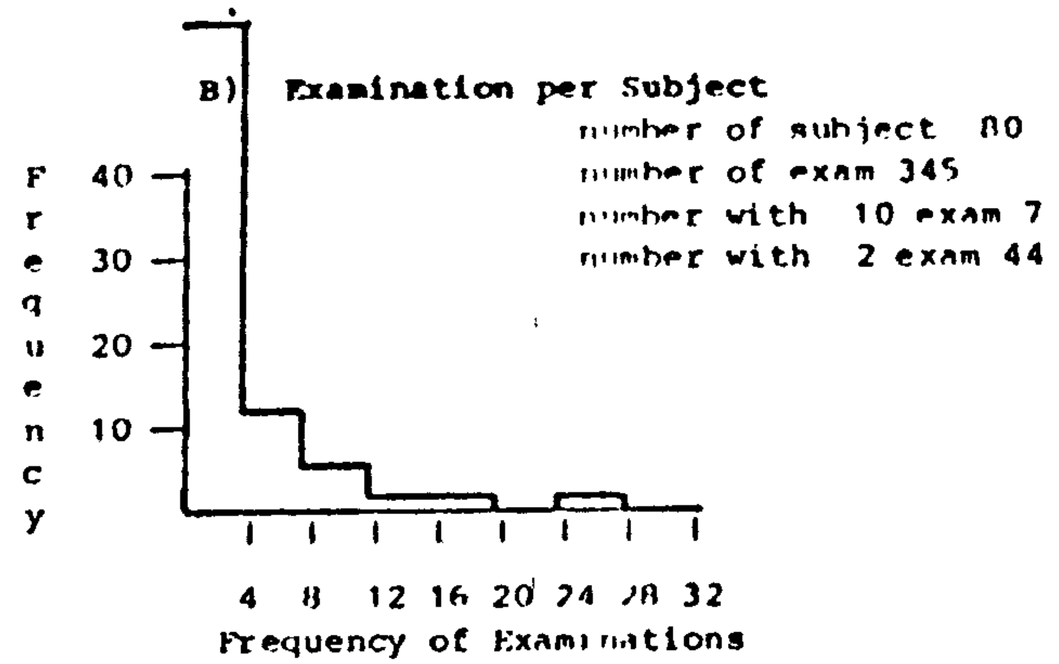
4.3 RESULTS

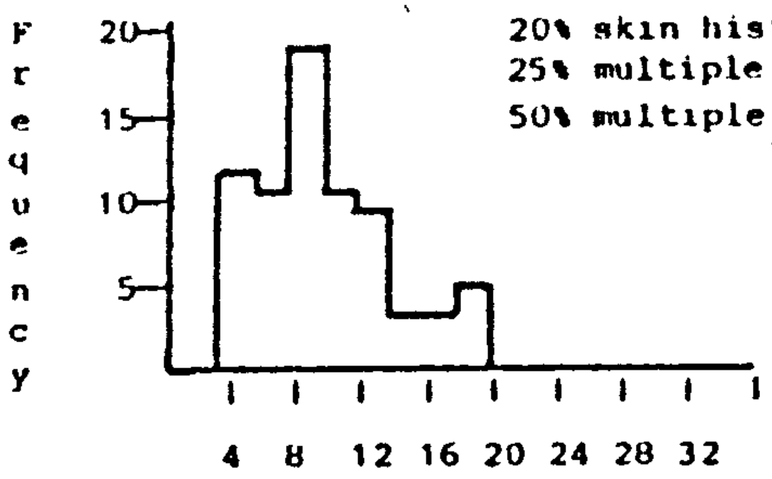
4.3.1 Test Population

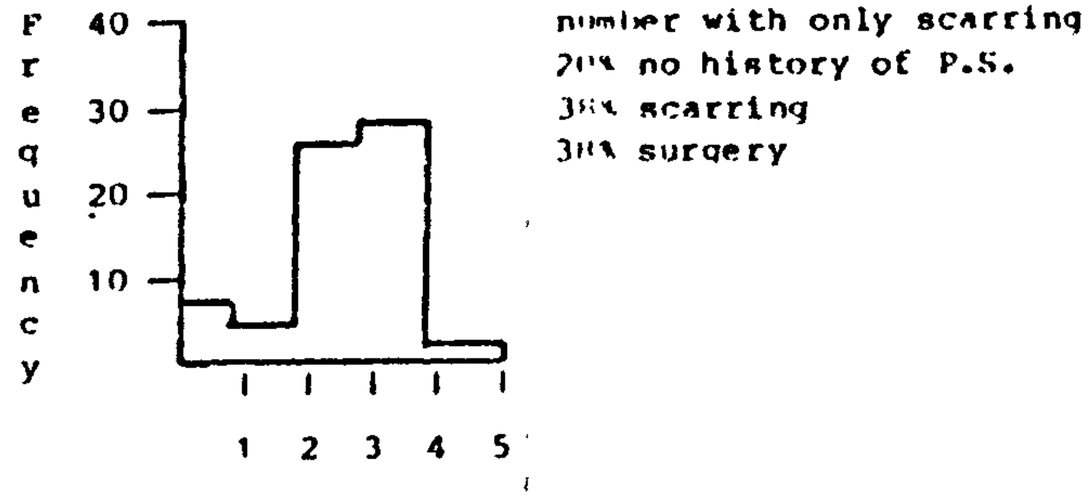
Four histograms were prepared to describe the study population, see Figure 4.7. The study population was predominantly young, 78% being under 25 years (the programme's prime mandate was to treat the Centre's Spina Bifida population). Half of the subjects (45) were seen once or twice, either through a screening procedure, which included a baseline examination followed by a sitting period and reexamination, or for an annual review. Another group of 27 patients were seen on three to ten occasions.

FIGURE 4.7 POPULATION CHARACTERISTICS









Code	
1) clear skin	3) scarring
2) discolouration	4) surgical scars
	5) neuro vasc. flap

This usually constituted a small series of examinations, related to the custom fitting of a new seating system. A final group of seven patients were seen many times, because of recurrent problems.

A skin risk value was determined for each patient, by adding the coded values for his/her skin type at each of the five bony prominences (see Figure 4.7(C)). As the scoring was graded from 1-5, the minimum total score is five, and the maximum, 25. Seventy of the eighty subjects had data available for all sites (close up views for areameter studies did not always provide a full view of the sitting surface). From this sample, 20% had no previous history of pressure sores (ie. the minimum score of 5). Interpretation of the rest of this distribution is facilitated by considering the histogram of the most severely affected site. Again, 20% showed no previous history of pressure sores, while 38% had evidence of scarring, and another 38%, of surgical intervention.

It is important to describe the study population in pressure sore research, which, in this instance, was composed primarily of young patients with Spina Bifida, who often presented with severe spinal deformities and hip dislocations. For this reason, a large number were described as "one buttock" sitters, who tended to develop chronic pressure sores over one of the ischial tuberosities. The physical deformities of these patients were severe because of the interference in normal growth patterns.

4.3.2 Interdependence of the Tissue Gradings

The tissue grading was based upon photographic data which recorded both surface scarring and skin colour. The latter measure was subject to the following sources of error; changes in film type, changes in film processing and colour shifts due to light

sources and projection mechanisms. To reduce these factors the same film and development laboratory were used throughout the research programme and all films were reviewed on the same microfiche projector.

To determine whether or not the two grading systems were independent. A bivariate frequency distribution was compiled, see Table 4.4. The following three hypotheses were then tested:

H_o tissue type and condition are equivalent;

H_1 tissue type and condition are partially interdependent; and

H_2 tissue type and condition are completly independent or random.

H_o was tested by comparing the actual frequency distribution with the theoretical distributions which would be associated with either H_o or H_2. It was not considered feasible to test directly for H_1 without theories to suggest expected distributions. The data were obtained under the following constraints:

i) include only post-sitting examinations;

ii) include only one sample per site per person; and

TABLE 4.4 TISSUE QUALITY DISTRIBUTION

TISSUE TYPE	Tissue sites: LIT - S	LIT - S	LIT - S	LIT - S	
	Tissue Condition: 1	2	3	4	TOTALS
1	9 - 4 13	2 - 3 5	2 - 5 7	1 - 1 2	14 - 13 27
2	8 - 4 12	4 - 8 12	4 - 3 7	4 - 1 5	20 - 16 36
3	6 - 4 10	3 - 4 7	0 - 0 0	- - - NA	9 - 8 17
4	20 - 22 42	3 - 9 12	1 - 0 1	- - - NA	24 - 31 55
TOTALS	43 - 34 77	12 - 24 36	7 - 8 15	5 - 2 7	66 - 68 135

ANALYSIS

The number of possible tissue quality combinations (4 x 4)- 2 = 14
The number in which TT gt TC (6)
The number in which TT = TC (3)
The number in which TT lt TC (5)
The frequency of distribution under random theory: H_2

$$H_2 = 135 \div 14 = 9.6$$

TABLE 4.5 HYPOTHESES TESTING

Frequency Comparison	Theoretical H_0	Theoretical H_2	Actual Frequencies	% Deviation from H_0	% Deviation from H_2
TT gt TC	0	57	84	NA	+32 %
TT = TC	135	28	25	-81 %	-10 %
TT lt TC	0	49	49	NA	-55 %

iii) collect data only for the left ischial tuberosity and the sacrum.

The total frequencies deviated both from the null hypothesis by 81% and that of complete independence by 32% for gradings of TT > TC and 10-0 % for gradings where TT < TC. There appears to have been an interrrelationship between the grading of tissue type and condition when the tissue had previous scarring but wa not acutely inflamed. This circumstance was true for approximately half of the samples (TT > TC).

This result implies that there were more occasions where the tissue, although previously irreversibly damaged, appeared to respond to loading without further compromise (tissue conditions 1 + 2 constitutes 84% of the samples). Since the tissue type and condition were graded on different visual characteristics, it was considered appropriate to treat them as independent variables.

4.3.3 Distribution of Trauma

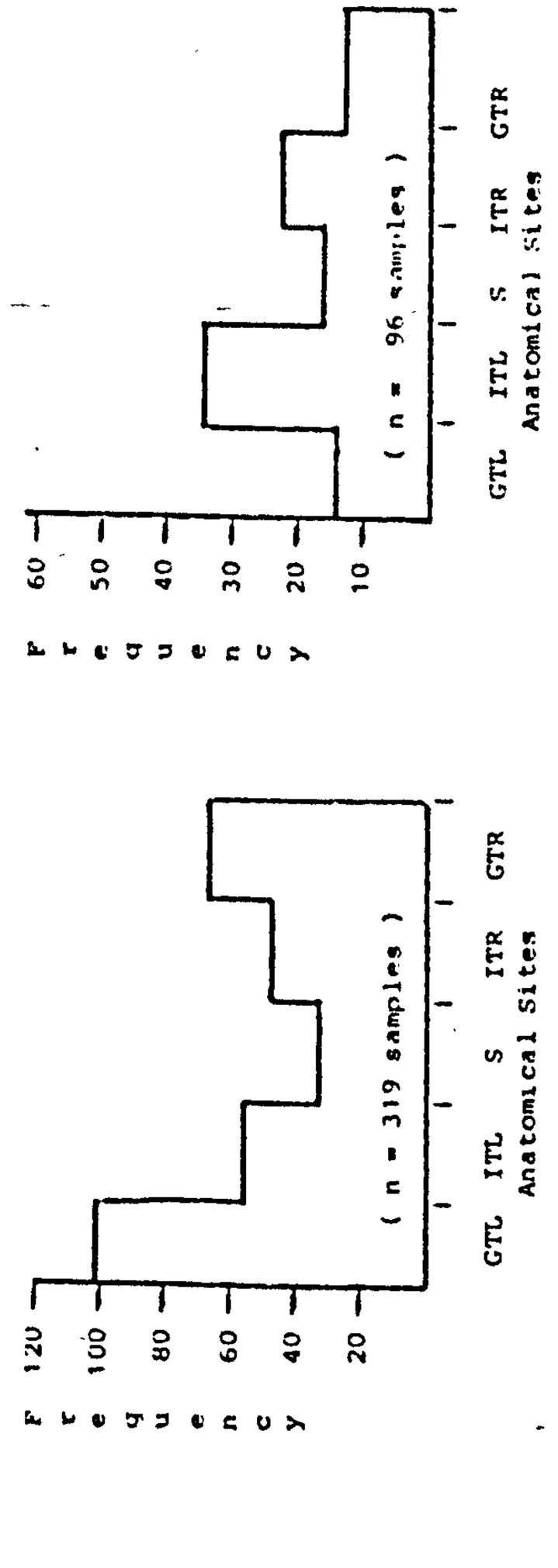
The maximum temperature data were compressed, (Table 4.6), to compare the data for each combination of tissue type and tissue condition. The numbers of subject samples (N), and of examination samples (n), are listed to highlight situations where one subject might dominate the results and skew the distribution, (for example, the four samples for the tissue quality combination 51, are from one subject).

The data strings for each anatomical site were tabulated independently, regrouped by tissue type and condition. The anatomical distribution of tissue types is displayed in Figure 4.8 as a composite of four histograms A) Good Tissues, B) Discoloured

TABLE 4.6 MAXIMUM TEMPERATURE VS TISSUE QUALITY

TT/TC	Subj. N	Sites n	Ave. Maximum Temp.	S.D.(σ)	Frequency at Sites GTL	ITL	S	ITR	GTR
11	48	272	32.4	1.4	96	42	27	31	76
12	19	44	33.5	1.3	6	13	5	14	6
13	3	3	33.Ø	1.7	Ø	Ø	1	Ø	2
14	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø
15	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø
21	19	65	32.6	1.1	1Ø	23	1Ø	12	1Ø
22	15	28	33.5	1.3	3	9	4	1Ø	2
23	2	2	32.5	3.5	Ø	2	Ø	Ø	Ø
24	1	1	36.Ø	Ø.Ø	Ø	Ø	1	Ø	Ø
25	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø
31	22	86	32.6	1.2	13	13	24	19	17
32	17	64	33.6	1.2	9	21	7	22	5
33	11	4Ø	34.3	1.1	1	7	19	12	1
34	12	25	35.4	1.3	3	4	15	1	2
35	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø
41	11	28	33.2	1.Ø	3	3	1Ø	5	7
42	1Ø	15	34.4	1.2	2	4	2	4	3
43	11	35	34.7	1.5	1	9	12	8	5
44	2	5	36.Ø	Ø.7	Ø	Ø	3	2	Ø
45	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø
51	1	4	33.1	1.1	Ø	Ø	Ø	4	Ø
52	1	2	31.5	2.1	Ø	Ø	Ø	2	Ø
53	1	1	33.Ø	Ø.Ø	Ø	Ø	Ø	1	Ø
54	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø
55	Ø	Ø	Ø.Ø	Ø.Ø	Ø	Ø	Ø	Ø	Ø

FIGURE 4.8 FREQUENCY OF TISSUE TYPE BY ANATOMICAL SITE



Tissues, C) Scarred Tissues and D) Surgical Sites. There were only two patients who had had the neuro-vascular flap procedure, type 5, In all of these conditions, the incidence of trauma to the ischial tuberosities appears to have been twice as frequent as for the greater trochanters, and 10% less frequent then for the sacrum.

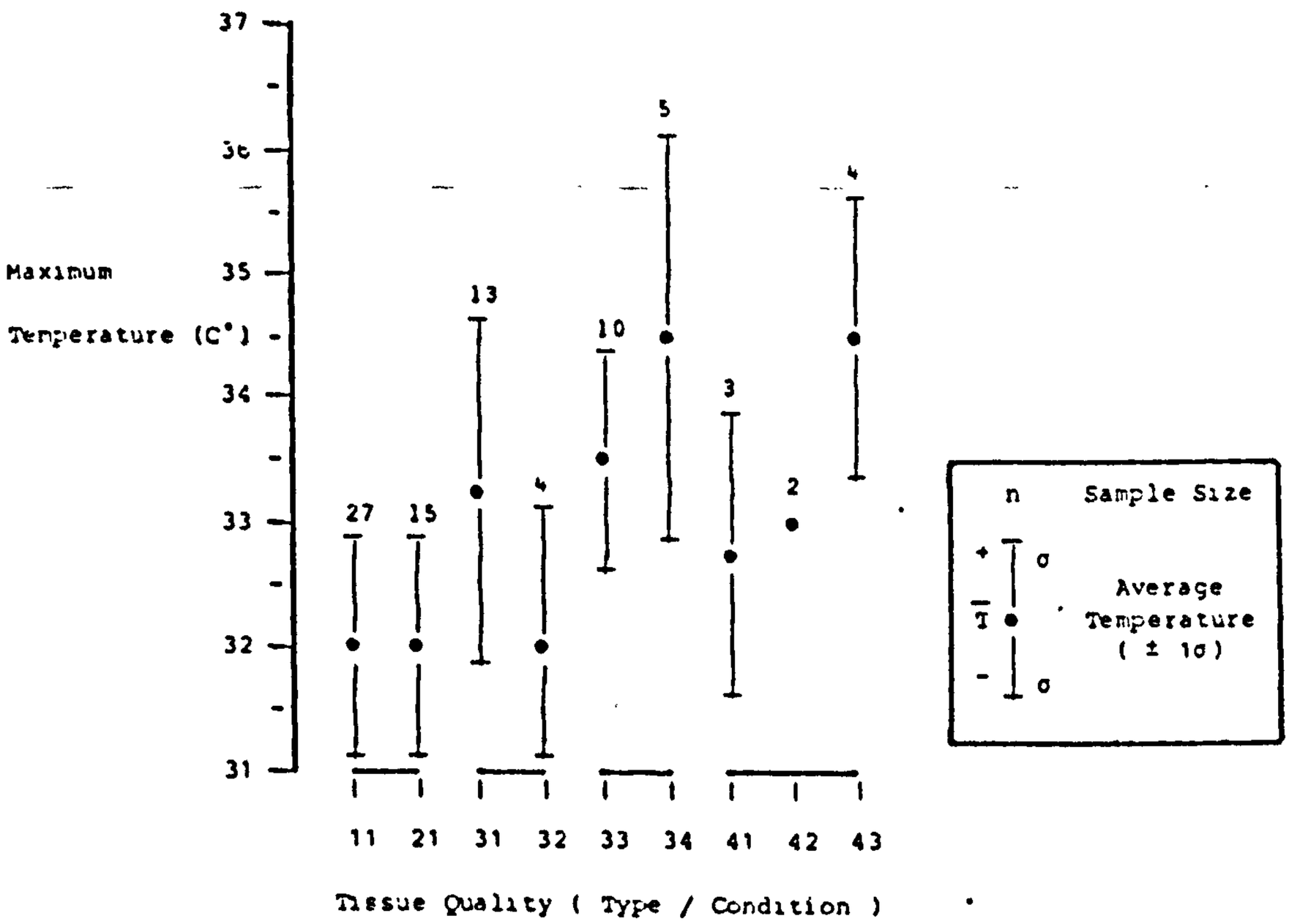
There was no left or right bias for pressure sore incidence, although the right ischial tuberosity was several percent higher in the incidence of scar tissues and surgical sites. The change in incidence of sacral trauma, (discoloured tissue at 16%, while both scarred and surgical sites were at over 30%) is probably due to the difficulty of assessing skin colour in the intertriginous zone of the perineum.

From these figures, it can be seen that 75-80% of the sitting trauma for this population occurred over the ischial-sacral bony complex. Although the data are not available in this particular analysis, it might be expected that the sacral lesions are most commonly found in conjunction with that high level of lesion, which results in a slouched kyphotic posture, with the pelvis in a tucked position.

4.3.4 Maximum Temperature versus Tissue Quality

Baseline examinations were used to provide an indication of the patient's tissue quality prior to conducting sitting trials. An initial analysis was conducted to determine whether or not any associations could be observed between clinical grading of tissue quality and skin temperature. Samples were selected from baseline examinations plotting averages and standard deviations for groupings of tissue quality grades, see Figure 4.9. If the pressure sore trauma resulted in either temporary increases in superficial blood supply, increases in resting skin temperature would be expected.

FIGURE 4.9 BASELINE MAXIMUM TEMPERATURES VERSUS TISSUE QUALITY



These temperature changes may be associated with the clinical decisions related to the safety of subject sitting. The thermographic guidelines defined by this techniques are based upon describing clinical practice and not on correlates with physiological parameters.

INTERPRETATION OF BASELINE EXAMINATIONS

TEMPERATURE RANGE	CLINICAL RECOMMENDATION
<33°C	safe at present sitting times
33°C - 34°C	caution, reduce sitting time
>34°C	unsafe, stop sitting until tissues cool

A second examination was conducted to identify the same type of guidelines for post sitting examinations. In Figures 4.10 and 4.11, the maximum temperature values were plotted with groupings of tissue types, and as a gradient of tissue conditions within each group. The points were each plotted with an error bar of plus or minus one standard deviation.

The large standard deviations were due in part to the variability of the measured phenomena, and in part, to lumping of

FIGURE 4.10 MAXIMUM TEMPERATURE VERSUS TISSUE QUALITY

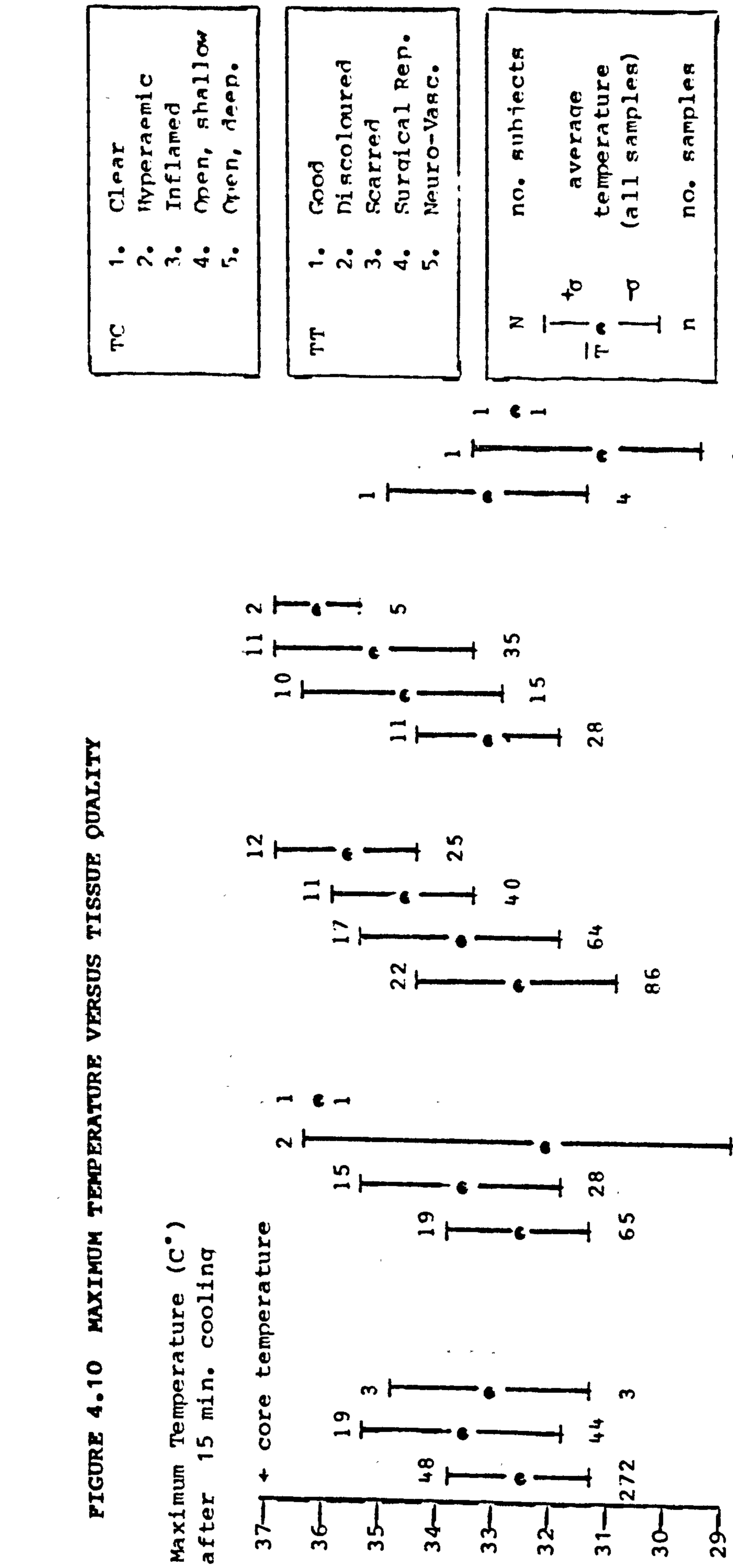
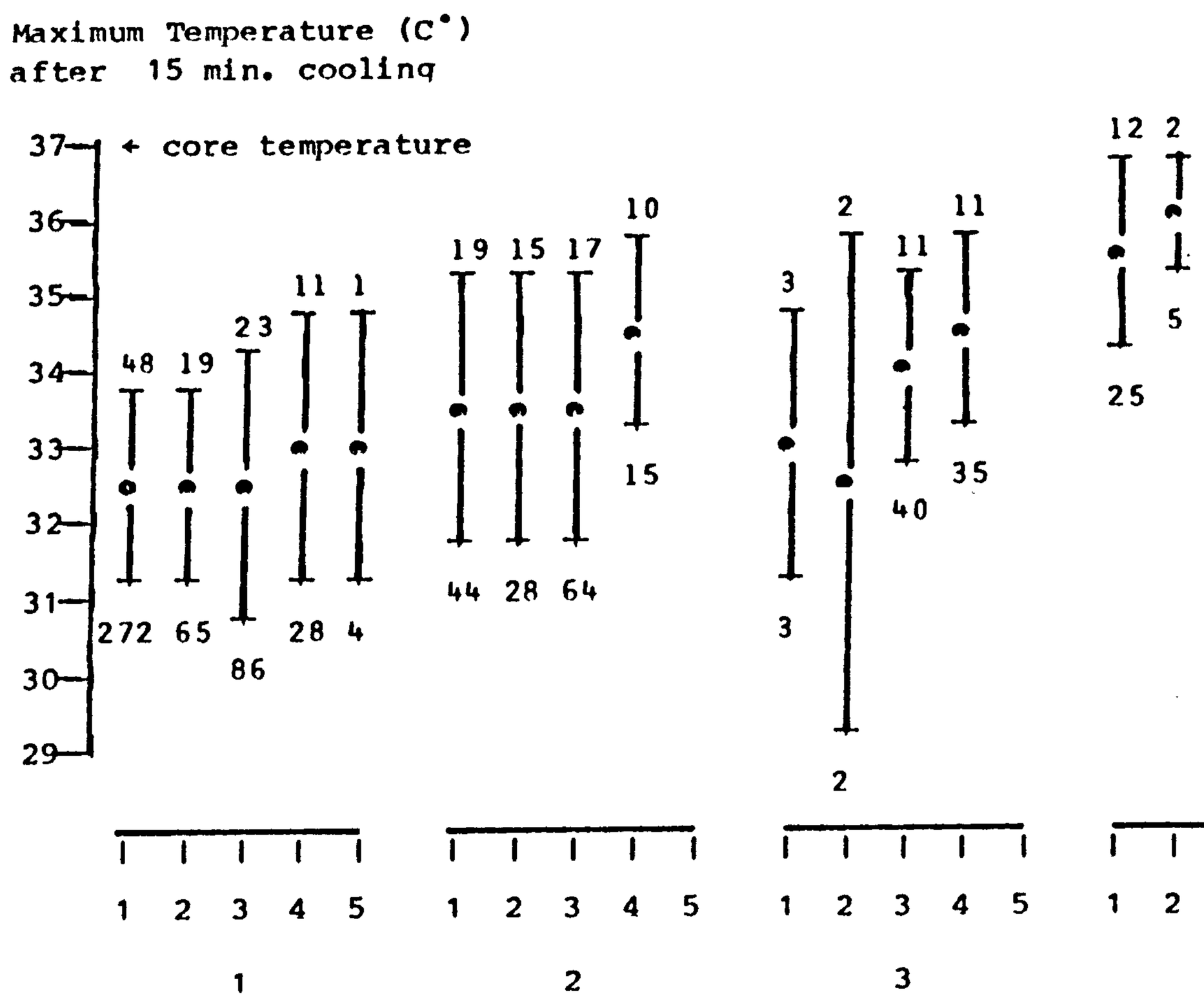


FIGURE 4.11 MAXIMUM TEMPERATURE VERSUS TISSUE QUALITY



TC	1.	Clear
	2.	Hyperaemic
	3.	Inflamed
	4.	Open, shallow
	5.	Open, deep.

TT	1.	Good
	2.	Discoloured
	3.	Scarred
	4.	Surgical Rep.
	5.	Neuro-Vasc.

N	no. subjects
$\bar{T}$	average temperature all samples
$\pm\sigma$	
n	no. samples

(TT) Tissue Type

(TC) Tissue Condition

Tissue Quality Coding

all test conditions. Any association demonstrated between temperature and individual tissue quality parameters would have to overwhelm the influence of the other variables such as sitting time, seat type and intersubject variability.

Comparing Figure 4.10 and 4.11, there appears to be a stronger relationship between the tissue's condition, and the fifteen minute maximum temperature, than there is with the tissue type. This suggests that a previous history of tissue trauma to a particular site is not so important a predictive factor of tissue tolerance, as is its current condition.

A second aspect of these figures is the relationship between absolute temperature and tissue condition. Are there critical temperature ranges which could be considered as warnings? In Figure 4.11, the grouped sets of data, given approximate temperature ranges based on the lowest and highest values encompassed by the error bars, appear to increase by 1C°, as the tissue deteriorates from one grade level to the next. In comparison, the following guidelines have evolved from four years of subjective clinical experience.

INTERPRETATION OF SITTING EXAMINATIONS

TEMPERATURE RANGE	CLINICAL RECOMMENDATIONS
<35°C	safe at current sitting times and seat type
35°C - 36°C	caution, reduction of sitting duration and review of seat type
>36°C	stop all sitting until tissue recovers

Although these guidelines are reinforced by the results of Figure 4.11, they were not considered complete enough to obviate the necessity for incorporating other pertinent clinical data into such judgements.

4.3.5 Evaluation of Seating Systems

To explore the possibility of evaluating seating systems thermographically, it was hypothesized that a seating system which created severe ischaemic conditions would also demonstrate a positive relationship between sitting time and skin temperature.

This is based on the assumption that the more severe the ischaemic insult, the greater the hyperemic reaction and, correspondingly, the hyperthermic reaction. The evaluation trials would therefore seek to measure any such degree of association.

For this purpose the data were grouped into four categories a) all samples, b) baseline examinations, c) sitting times only and d) by seat systems. Since the measurements are ratio values, the Pearson correlation coefficient (r_p) and the percent association ($100\ r_p^2$) were calculated, see Table 4.7.

There was a weak correlation between sitting times and maximum temperatures sampled after 15 minutes. For all seat types grouped together with baselines, there was significant correlation at the 5% level. This result might simply be representative of a spread between two populations of data, and not of a continuous trend. Two seat types, (hammocked seat and bean bag), showed a correlation at the 5% level. This may be a sensitive measure of seat safety indicating as it does that the longer a seat is used, the more prolonged the skin over the weight bearing areas remains at an elevated temperature. If the seating system achieves a loading and unloading cycle, indefinitely tolerable for the buttock tissues, such a correlation would not be expected. It must be recognized that each type of cushion will produce some unique pattern of ischaemia and thermal exchange with the tissues, e.g., contrast the insulating effect of foam and conductive cooling of water cushions.

TABLE 4.7 CORRELATION OF SITTING TIME AND SKIN TEMPERATURE BY SEAT TYPE

Grouping Criteria	N	Subj Samples n	Pearson Correlation r	% Degree Association $(100r^2)$
a) All Samples	57	720	* 0.252	6.4
b) Baselines	24	218	0.000	
c) All Sitting Times	52	502	0.128	1.6
d) individual seats				
hammocked canvas	7	39	* 0.387	15.0
tempra-foam (T41)	0	0	0.000	
contoured foams	9	67	-0.000	
contoured foam (T41)	3	40	-0.021	
contoured foam (T51)	13	83	-0.025	
air flotation (Roho)	11	65	0.055	0.3
Roho on a base	10	143	0.147	2.2
bye-bye	1	5	0.000	
bye-bye on a base	0	0	0.000	
bean bag	2	15	* 0.559	31.3
gel	3	24	0.143	2.0
gel on a base	2	10	0.033	0.1
rubber ring	1	5	0.000	

Interpretation:

Pearson correlation coefficient (r), two tailed test significant at the .02 level (*)

Percent degree of association (r^2 X 100)

A further sample of data was considered for the Roho cushion limiting the skin quality to (1/1 and 2/1), and the sample sites to the ischial tuberosities, Figure 4.12 . This seat had the largest available sample size of 10 subjects and 143 site examinations. However, when the additional constraints of tissue type and condition were included as well as sitting time intervals, each point represented only two or three data points. Given these restraints, no time dependent trend was observed for skin temperatures.

In addition, baseline temperatures were compared for each seat type under the same selection constraints, Figure 4.12 . No variation was observed greater than 1 standard deviation of the means. The tissue which had no observable trauma showed no elevation in temperature. Most values fell within the range of 31.5°C to 32.5°C .

4.3.6 Subject to Subject Relative Maximum Temperature Analysis

The previous analyses considered tissue samples independently of one another. This section reviews the trends, when recalculated with relative, and not absolute temperatures. The data were screened to operate on those sets which had values for each of the five bony prominences. With this new subset of data the temperature values were recalculated using the lowest maximum temperature as a zero reference for each examination. This meant that there was a "floating zero" reference, dependent upon the subject and the previous sitting conditions. This processing of the data eliminated the possible influence of general temperature level changes. These values were interdependent, so that the relative, or

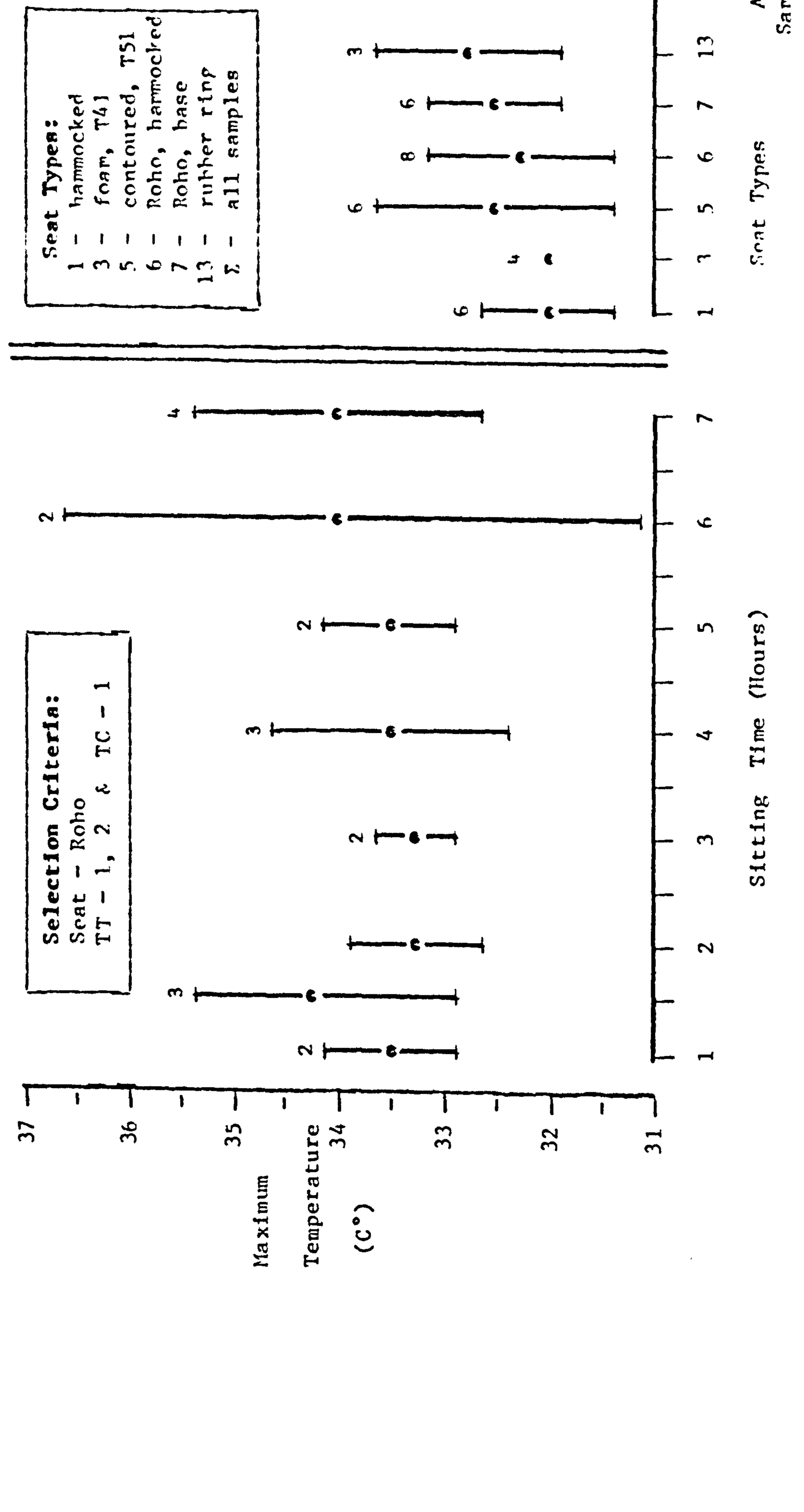


FIGURE 4.12 INTERDEPENDENCE OF SITTING TIME AND MAXIMUM TEMPERATURE

difference temperatures, reflected the influence of differential weightbearing on the bony prominences.

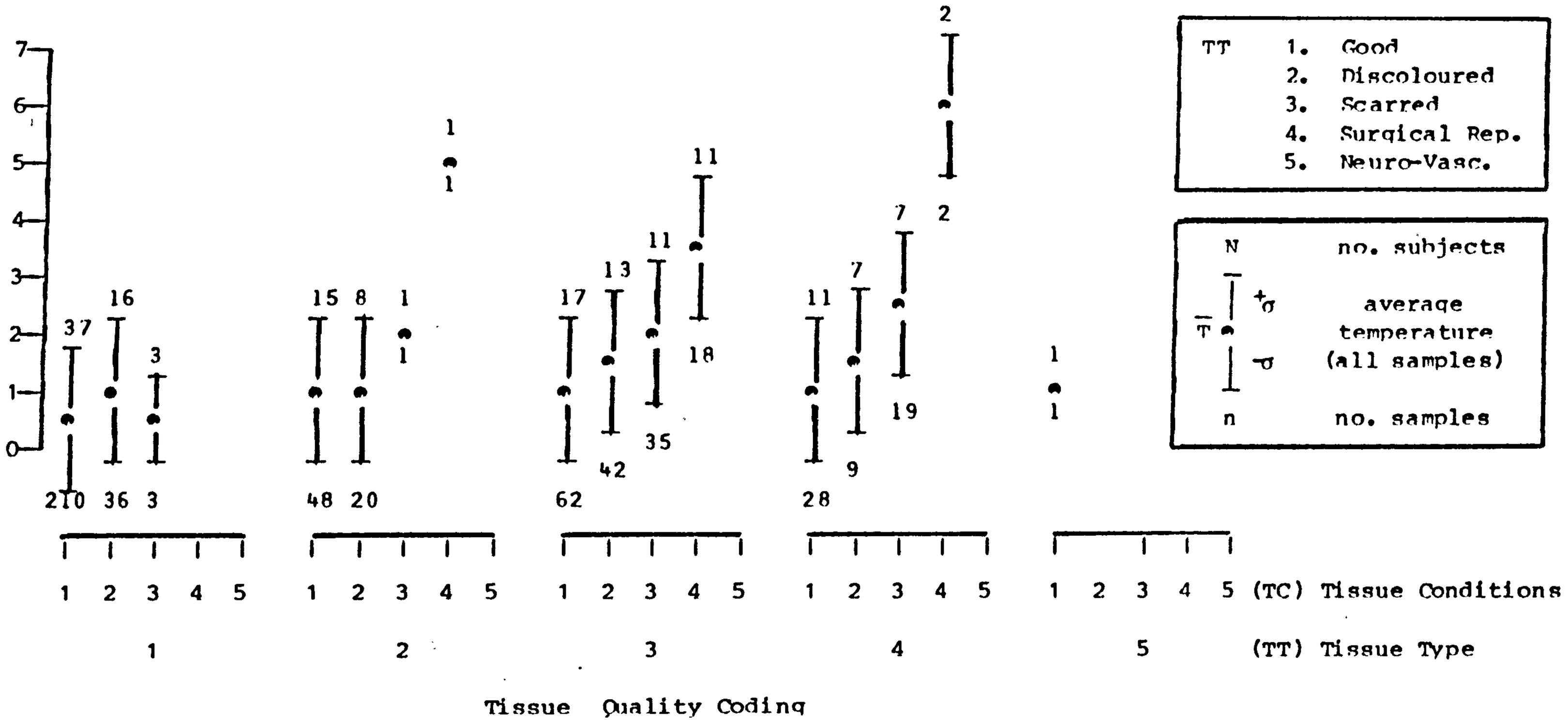
It was hypothesised that if all of the tissue quality and loading parameters were equal for all of the weightbearing bony prominences, the skin temperature would also be equal, and the relative temperatures zero. The average relative temperatures are presented in Table 4.8. . It was not surprising that tissue types graded as "good", did not fall into the more severe levels of tissue condition. There were only two patients with neurovascular flaps, providing too few sample data points for calculations. The distribution of tissue quality states per anatomical site did not change from the absolute temperature analysis, except in the sample size.

The contents of Table 4.8 are displayed in Figures 4.13 and 4.14, plotting the mean relative temperatures of each tissue quality combination. Tissue conditions are grouped togeather in Figure 4.13 and tissue types in Figure 4.14. The standard errors (σ) were greater than for the previous absolute temperature analysis. The large scatter indicated that this measure of the skin temperature is quite variable. The tissue condition appears to be more closely related to the relative temperature changes than the tissue type. Non-inflamed tissue had a mean relative temperature of +1C° with (σ = 1C°). From this, it can be said that changes greater than ±2° would fall outside the 95% confidence limit for healthy, undamaged tissue. When the relative temperature difference is greater than 3°C, the patient's skin is probably inflamed, and at risk. This great a temperature difference can be readily detected by either hand held radiometers or by touch.

TABLE 4.8 RELATIVE MAXIMUM TEMPERATURE VS TISSUE QUALITY

TT/TC	Subj. N	Sites n	Average Temp.	Relative S.D.(σ)	Frequency at Sites GTL	ITL	S	ITR	GTR
11	37	21ø	ø.7	ø.9	71	3ø	22	25	62
12	16	36	1.1	1.1	5	11	4	11	5
13	3	3	ø.6	ø.5	ø	ø	1	ø	2
14	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
15	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
21	15	4ø	1.ø	1.1	7	18	9	9	5
22	8	2ø	1.1	1.ø	2	6	3	7	2
23	1	1	2.ø	ø.ø	ø	1	ø	ø	ø
24	1	1	5.ø	ø.ø	ø	ø	1	ø	ø
25	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
31	17	62	ø.9	1.1	1ø	8	22	1ø	12
32	13	42	1.5	1.5	4	13	5	17	3
33	11	35	2.2	1.2	1	6	17	1ø	1
34	11	18	3.6	1.4	2	3	1ø	1	2
35	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
41	11	28	1.1	ø.8	3	3	1ø	1ø	7
42	7	9	1.7	1.ø	2	2	ø	ø	2
43	7	19	2.6	1.4	ø	6	2	2	4
44	2	2	6.ø	1.4	ø	ø	1	1	ø
45	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
51	1	1	1.ø	ø.ø	ø	ø	ø	ø	ø
52	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
53	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
54	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø
55	ø	ø	ø.ø	ø.ø	ø	ø	ø	ø	ø

FIGURE 4.13 RELATIVE MAXIMUM TEMPERATURE VERSUS TISSUE QUALITY



TC	1.	Clear
	2.	Hyperaemic
	3.	Inflamed
	4.	Open, shallow
	5.	Open, deep.

TT	1.	Good
	2.	Discoloured
	3.	Scarred
	4.	Surgical Rep.
	5.	Neuro-Vasc.

N	no. subjects
$\bar{T}$	average temperature (all samples)
$+\sigma$	
$-\sigma$	
n	no. samples

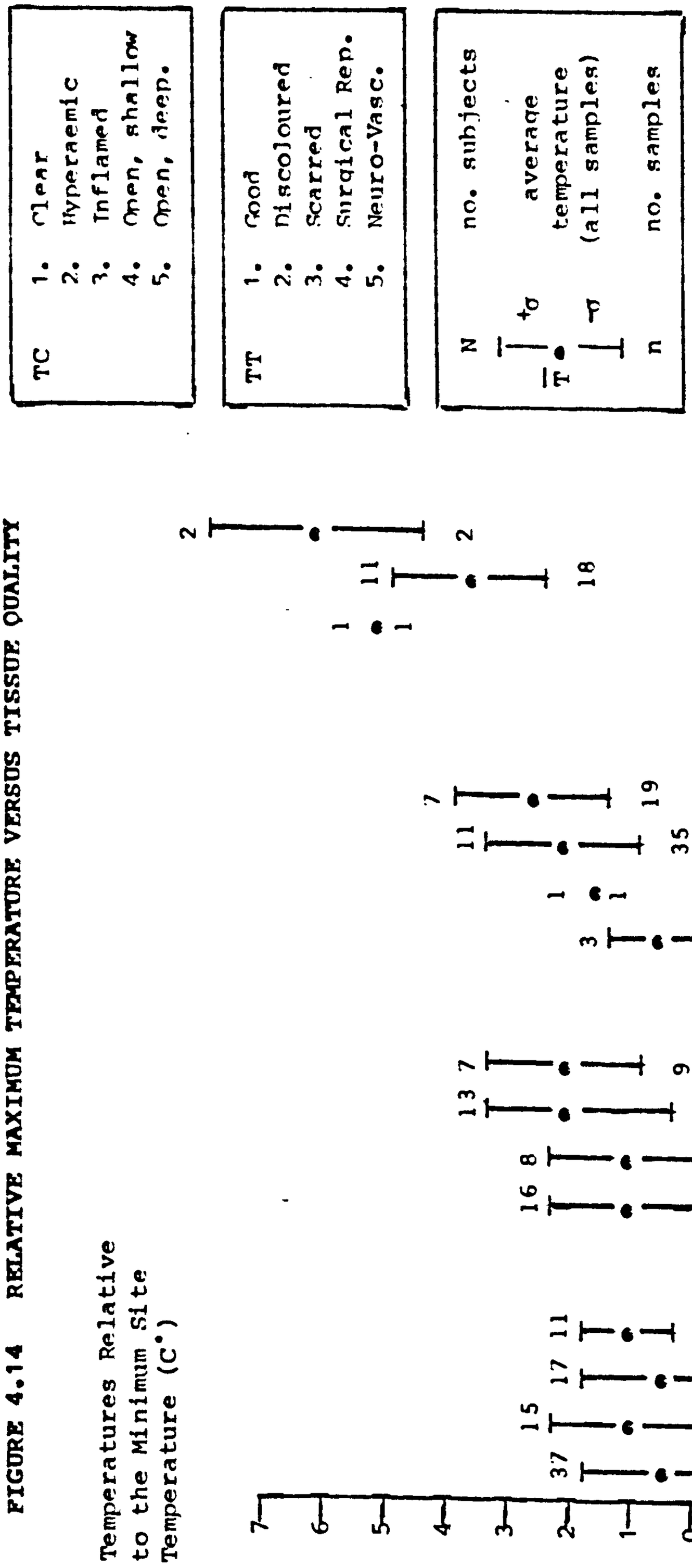


FIGURE 4.14 RELATIVE MAXIMUM TEMPERATURE VERSUS TISSUE QUALITY

Temperatures Relative to the Minimum Site Temperature (C°)

Inflamed tissues were found to have a local increase in temperature ranging from (+2 to +2.5C°), except for apparently healthy tissue (type - 1) which was inflamed from an acute stress (condition - 3), see Figure 4.14, resulting in a much smaller temperature increase (+0.6 ±0.6C°). The open pressure sore grade of tissue condition (4) ranged from (+2.2 to +7.5C°). It is noted, in comparison, that Barton (1973) recorded a temperature difference of +2.5°C between healthy tissue and the inflamed tissue surrounding an open sore. Under conditions of sitting stress, discoloured tissues may show this degree of relative increase. However, it should be noted that these relative temperatures do not reflect temperature gradients with the adjacent tissues.

Comparisons of sitting times and skin relative skin temperature were less sensitive than found with the absolute temperatures, see Table 4.9 . However, the same trend was observed for the bean bag seating system.

4.4 DISCUSSION

4.4.1 Significance of the Thermographic Data

The analyses in this chapter sought to identify critical absolute or relative temperature criteria which could be used within the context of a clinical seating programme. The thermograph contains spatial, temporal and thermal information for any target surface. These data must be reduced by orders of magnitude to provide useful information. The choice of "how" and "what" to quantify, requires insight, experimentation and experience. In the first stage of this process, described in this chapter, simplifying assumptions were required to facilitate the interpretation of maximum skin temperatures. It was assumed that such data

TABLE 4.9 CORRELATION OF SITTING TIME AND RELATIVE SKIN TEMPERATURE BY SEAT TYPE

Grouping Criteria	Subj. N	Samples n	Pearson Correlations r	% Degree Association $100r^2$
a) All Samples	40	355	-0.024	
b) Baselines	19	160	0.000	
c) All Sitting Times)	41	395	-0.025	0.1
d) individual seats				
no cushion	6	35	-0.141	2.0
foam, polyurethane	0	0	0.000	
foam, tempra-foam (T41)	5	50	0.012	
T41 contoured (soft)	3	40	-0.081	0.7
T51 contoured (hard)	11	70	-0.004	
Roho (air flotation)	8	55	-0.016	
Roho on a base	8	85	0.168	2.8
Bye-bye (water flotation)	1	5	0.000	
Bye-Bye on a base	0	0	0.000	
Bean bag	2	15	* -0.484	23.4
Gel	2	20	0.157	2.5
Gel on a base	2	10	0.033	0.1
Rubber Ring	1	5	0.000	

Interpretation:
Pearson correlation coefficient (r) significant at the .02 level for the two tailed test (*)
Percent degree of association (r^2 X 100)

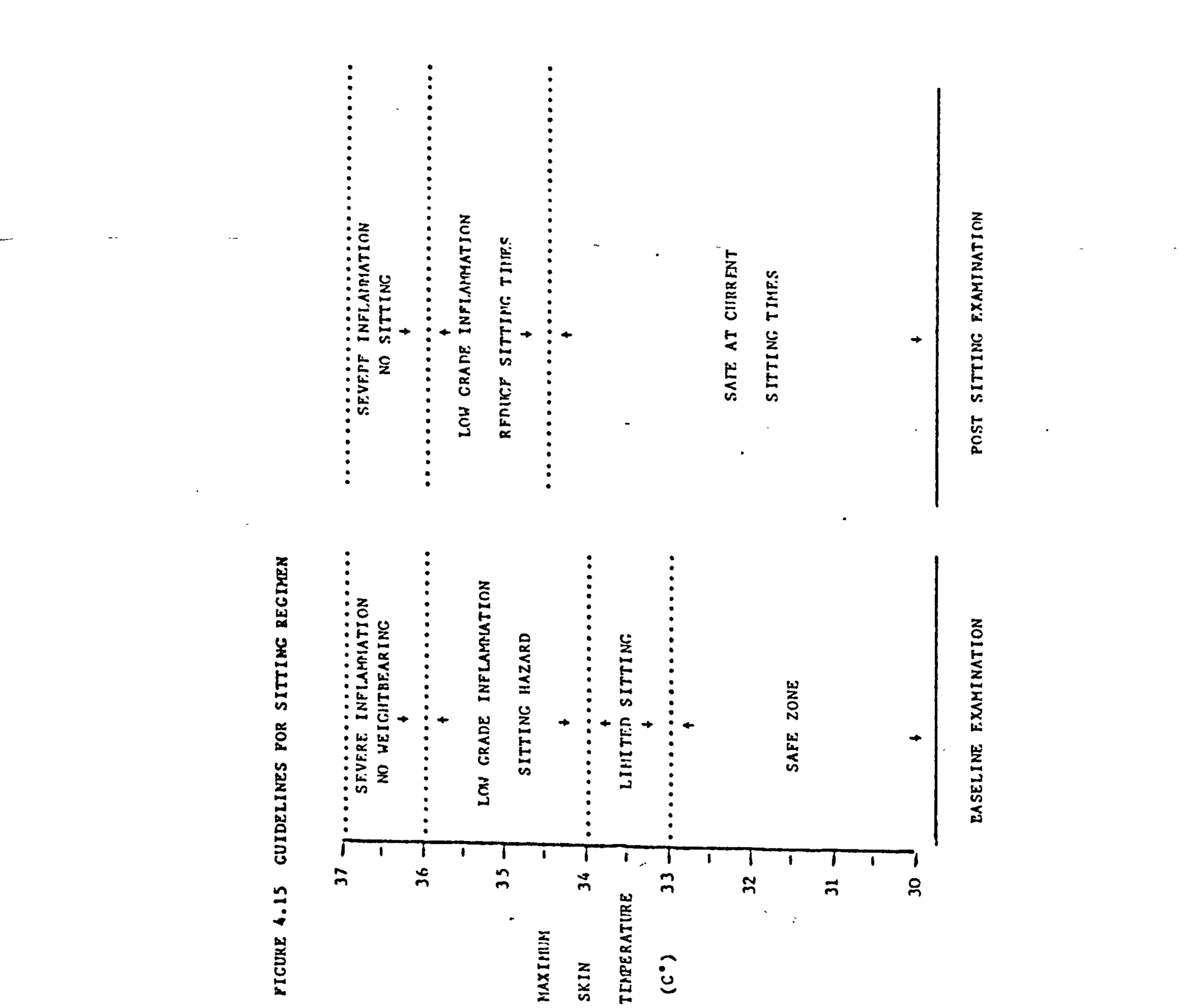


FIGURE 4.15 GUIDELINES FOR SITTING REGIMEN

represented differential cooling patterns, corresponding to localised blood flow changes.

In addition, it was assumed that the skin temperature was influenced by both the immediate tissue loading conditions and by the pathophysiologic changes which resulted from the traumatic history of the site. For these reasons, only partial or weak correlations were expected between selected pairs of parameters.

The plots of absolute and relative maximum temperatures vs. tissue type and condition confirmed that only weak trends were discernable at 68% confidence limits. This variation was considered inherent in both of the parameters being compared. Since there was no absolute reference against which to calibrate the tissue grading procedure, nor any quantitative alternative which was clinically practical, this photographic approach was a useful exercise.

The identification of skin responses indicating that the loading conditions or the tissue quality are not viable, is the main objective of the research. Unfortunately, the only direct evidence possible is that obtained by histological studies. Without this reference base, the interpretation of indirect measurement must be circumstantial, until sufficient numbers of tests permit the application of statistical measures to identify the significance of each parameter.

It has not been possible to demonstrate that there are specific absolute temperatures predicting tissue viability ; however, rough guidelines were developed to match the clinical practice which evolved over several years of observations, see Figure 4.15. There remains a requirement to conduct further basic research into the classification of tissue quality to clarify the significance of the

absolute skin temperatures. Classification of skin temperature response appears to be part of a multivariable relationship, which might require other measurements, such as blood flow. If the temperature changes describe the tissues response, one must be able to describe tissue quality parameters before attempting to interpret the response as expected and/or safe.

4.4.2 Quantitative Analysis

The digitization techniques employed in this chapter were unsatisfactory, with respect to the following scientific measurement requirements; 1) sampling times, 2) resolution, and 3) processing of the data.

There are two major routes to follow in this type of project: Management and processing of all the image data, or pre-filtering and processing of selected data. The second option was considered more practical and was approached by the use of an areameter automatically measuring isotherm areas. This development is presented in the next two chapters for normal subject trials in Chapter 5 and patient trials in Chapter 6.

4.4.3 Summary of Developments

The following contributions and findings were presented in this chapter.

1) A thermographic protocol for seating studies was presented along with a novel microfiche storage and retrieval system for thermograms.

2) The study population was defined in terms of age group, 78% being under 25 years. The prevalence of pressure sores with

respect to anatomical site was listed, (Sacrum 30%, Ischii 50%, Greater Trochanters 20%). No left or right bias was found.

3) The sampled maximum temperature data were considered highly variable for the following reasons: a) variability inherent in skin temperature data, and b) the grouping of all test conditions together, eg. sitting and baseline examinations.

4) Other authors, Rogers (1973), Goller (1971), and Roemer (1976) have tried to find a direct correlation between skin temperature fluctuation and tissue loading. No strong correlations were observed between sitting times and skin temperature except for the bean bag cushion. It may be necessary to include other measured parameters describing the tissue type to improve the reliability of such predictive risk tests. Further research is required to determine such relationships.

5) The variability of the data was such that all trends were only observed with error bars of one standard deviation. This method of collection skin temperature is not sensitive and/or selective enough to evaluate seating systems.

Automated data collection and analysis is required to fairly determine the full usefulness of thermographic techniques in the application.

CHAPTER 5: QUANTITATIVE TECHNIQUES AND ENVIRONMENTAL VARIABLES

5.0 INTRODUCTION

This chapter reports on the initial use of an areameter developed at the Defence and Civil Institute of Environmental Medicine (DCIEM) for seating evaluation. An experimental model, using normal subjects and experimental wheelchair seats, was employed to simulate an extreme range of ischial pressure conditions. In the initial series of experiments tests were conducted to determine the sensitivity of skin temperature to variations in sitting stress.

The environmental parameters of ambient temperature and relative humidity were varied in a second set of trials to ascertain the minimum control requirements for a clinical thermographic chamber. For this series of tests baseline and sitting trials were conducted at each of four ambient temperatures to compare the maximum range allowable within a hospital examination room. Several trials were also conducted introducing step changes in ambient temperature and relative humidity to determine the sensitivity of the quantitative skin temperature data to such ambient perturbations.

5.1 METHOD

5.1.1 Experimental Model

5.1.1.1 subjects

Four normal subjects participated in these experiments to permit the use of extreme levels of sitting stress without risking tissue breakdown. The morphology of the subjects, was determined

by skinfold thickness tests, and the subjects classified as follows; (A&B) - mesomorph, (C) - endomorph and (D) - ectomorph.

5.1.1.2 seating stresses

Three wheelchair seats were used to create four levels of ischial pressure designated I, II, III and IV, see Figure 5.1. Previous studies of pressure distribution over the buttocks during sitting have indicated that pressures are highest over the ischial tuberosities, (Houle (1969) and Souther (1974)), although it has also been shown that slight shifts in sitting posture can significantly alter local pressure distribution, Krouskop (1976) and Bush (1969). To minimize this effect, the wheelchair footplates were elevated so that the seated subject's weight was borne primarily through his ischial tuberosities. Although the maximum pressures were well in excess of the 26,7 kPa (200mmHg) range on the available pneumatic pressure sensor, the subjects reported an increase in discomfort for sitting stresses II through to IV.

The minimum stress level (I) was used to designate both the standing baseline and the unloaded ischial tuberosity on the cutout seat although these loading conditions were not identical. Stress level (II) designated the ischial pressures induced by a plywood base covered with one inch of polyurethane foam. The same seat was used without the foam, stress level (III) to produce a symmetrical high level of pressure and the cutout seat (IV) for asymmetrical loading, see Figure 5.1.

5.1.1.3 examination protocol

All four subjects stood for a minimum of 30 minutes prior to the 30 minute test sitting period to minimize the influence of any

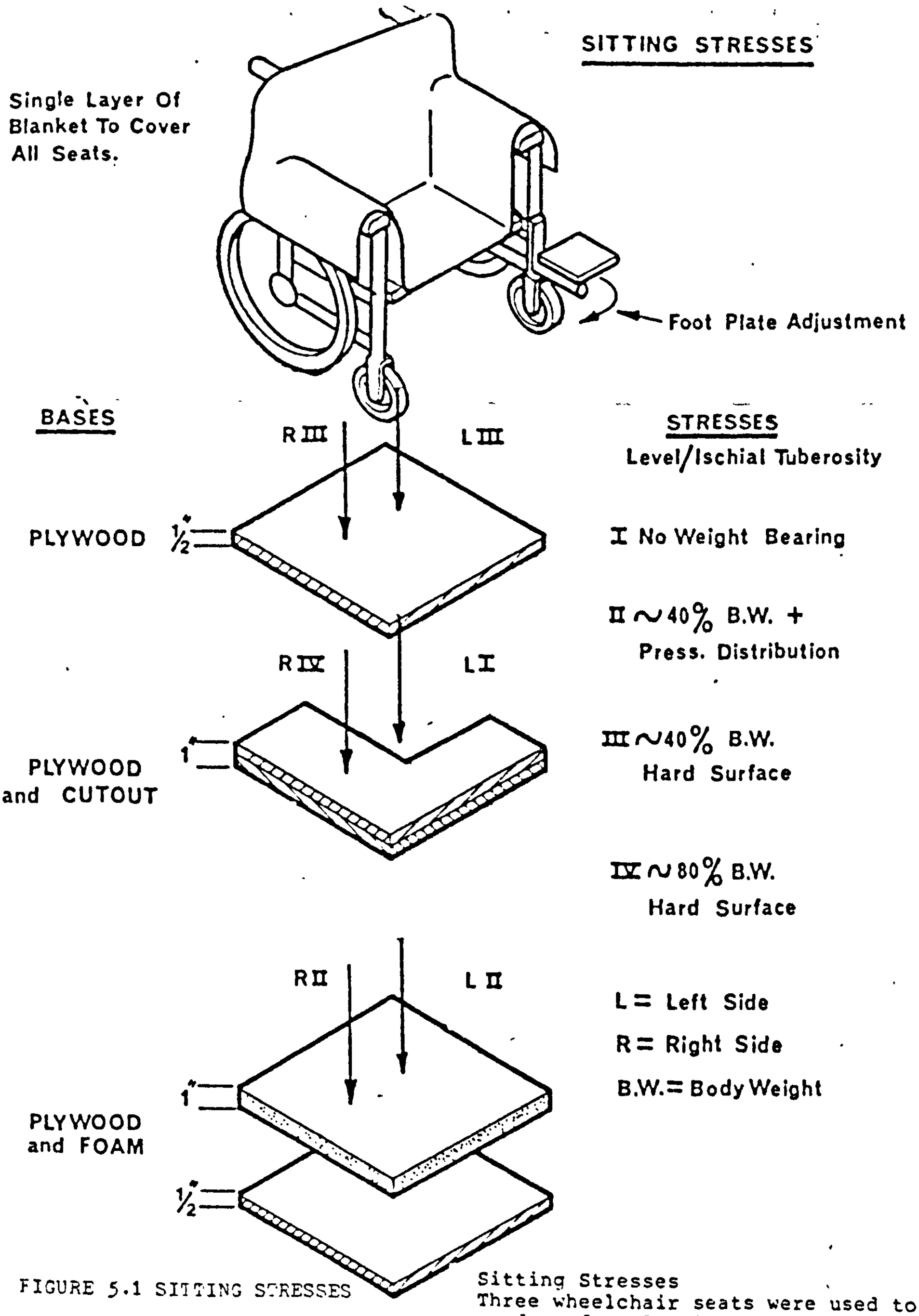


FIGURE 5.1 SITTING STRESSES

Sitting Stresses
Three wheelchair seats were used to produce four levels of stress.

previous sitting. Trials were conducted on the same subject in the morning and the afternoon of the same day with a recovery interval of several hours. Stress level IV was not used during the morning session to avoid stress carryover to the afternoon.

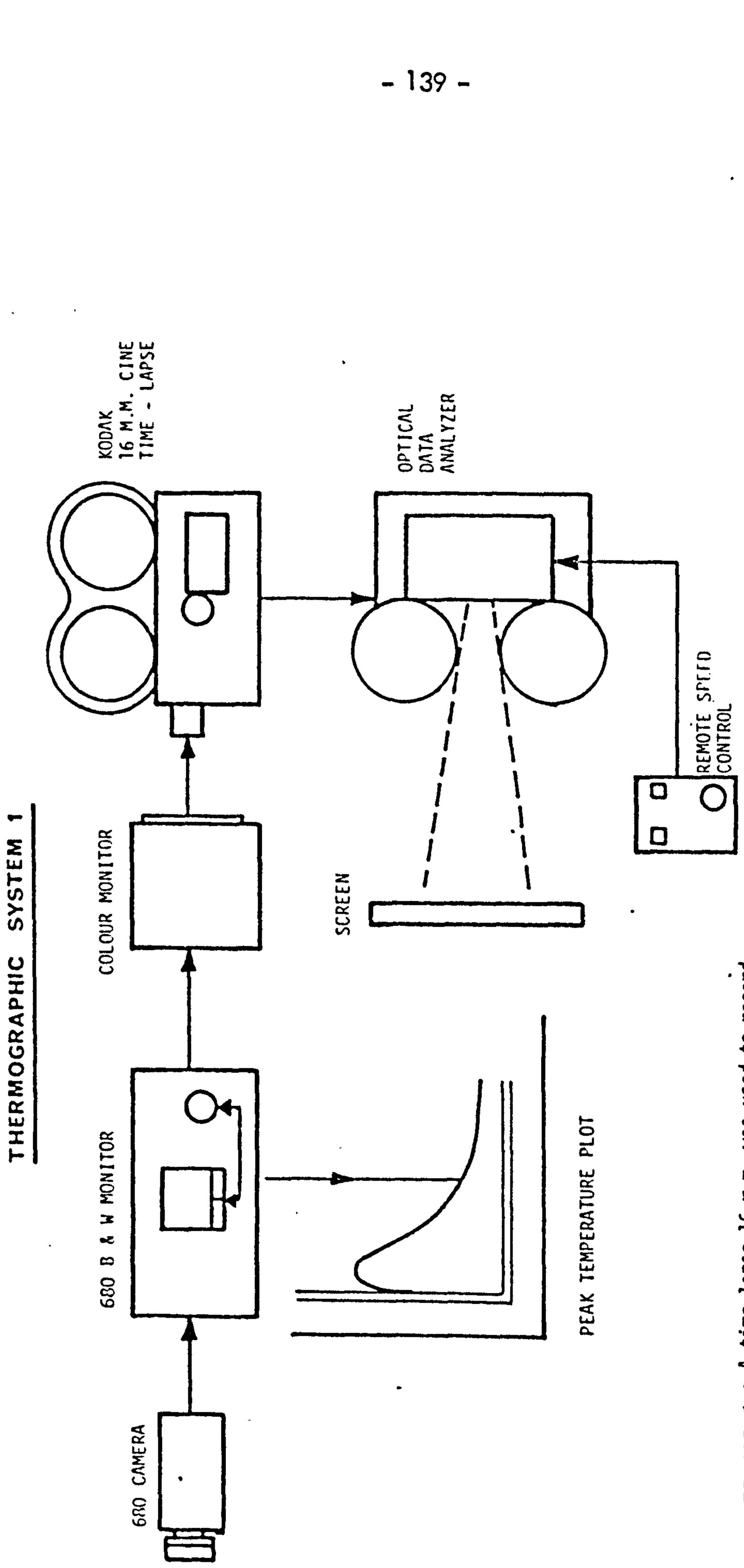
The trials were run in the DCIEM Tropical chamber which afforded independent control over a wide range of ambient temperatures and relative humidities. In order to prevent exposure of the subject to any transient temperature or humidity changes the entire sitting and observation cycle took place in the chamber. All subjects wore similar garments during the tests, namely, a shirt, light weight long trowser, briefs, shoes and socks. At the initiation of the thermographic examination, the subject transferred himself to the prone support bench after disrobing appropriately.

5.1.2 Instrumentation

5.1.2.1 thermographic system 1

Each of two thermographic systems were used to collect both qualitative and quantitative data. A 16mm cine camera was used to record the temperature patterns displayed on monitor 1 continuously, see Figure 5.2. The cine camera was a Kodak model 1 TM reflex special, adapted to record at 0.3 frames per second. These films were reviewed on an L-W International Photo Optical Data Analyser Model 224A MKV, which projected a non-flickering image at rates ranging from single pulse to 24 frames per second.

Quantitative data were obtained by an observer who determined the maximum temperature on the thermograph display by scanning the temperature scale with a manually adjusted 0.1 C° isotherm highlighter. The maximum temperature was located when the highlighting disappeared as the isotherm scan moved up the



THERMOGRAPHIC SYSTEM 1

FIGURE 5.2 A time-lapse 16 m.m. was used to record the complete examination cinematographically

temperature scale. The observed maximum temperatures were plotted by hand during the examination.

5.1.2.2 thermographic system 2

The second thermographic system, see Figure 5.3, consisted of an automatic isotherm areameter and a remotely controlled pan-tilt infrared camera. Thermographs were photographed in sequence, with automatic quantitative data sampling from the colour monitor which was connected to the DCIEM areameter. The areameter provided an analogue signal for each isotherm channel proportional to percentage area in the field of view. The data sampling window was highlighted and could be adjusted in size and location to permit the exclusion of portions of the screen not considered to be of interest in a quantitative analysis.

Contralateral comparisons were facilitated by the use of a preset splitting of the data window into two halves. Data was sampled independently from each side at specified time intervals to permit contra-lateral comparisons. A highspeed multichannel data acquisition system was used to digitize the signals for input data to the Hewlett-Packard microcomputer. The signals were then processed and stored on both magnetic and paper tapes.

5.1.3 Calibration

The camera in system 1 had the larger field of view, because of its greater distance from the subject. An AGA absolute temperature reference was set at 33°C., and the system was adjusted so that this temperature was midscale in a displayed temperature range of 10C° (from 28°C to 38°C). When trials were run at a sensitivity setting

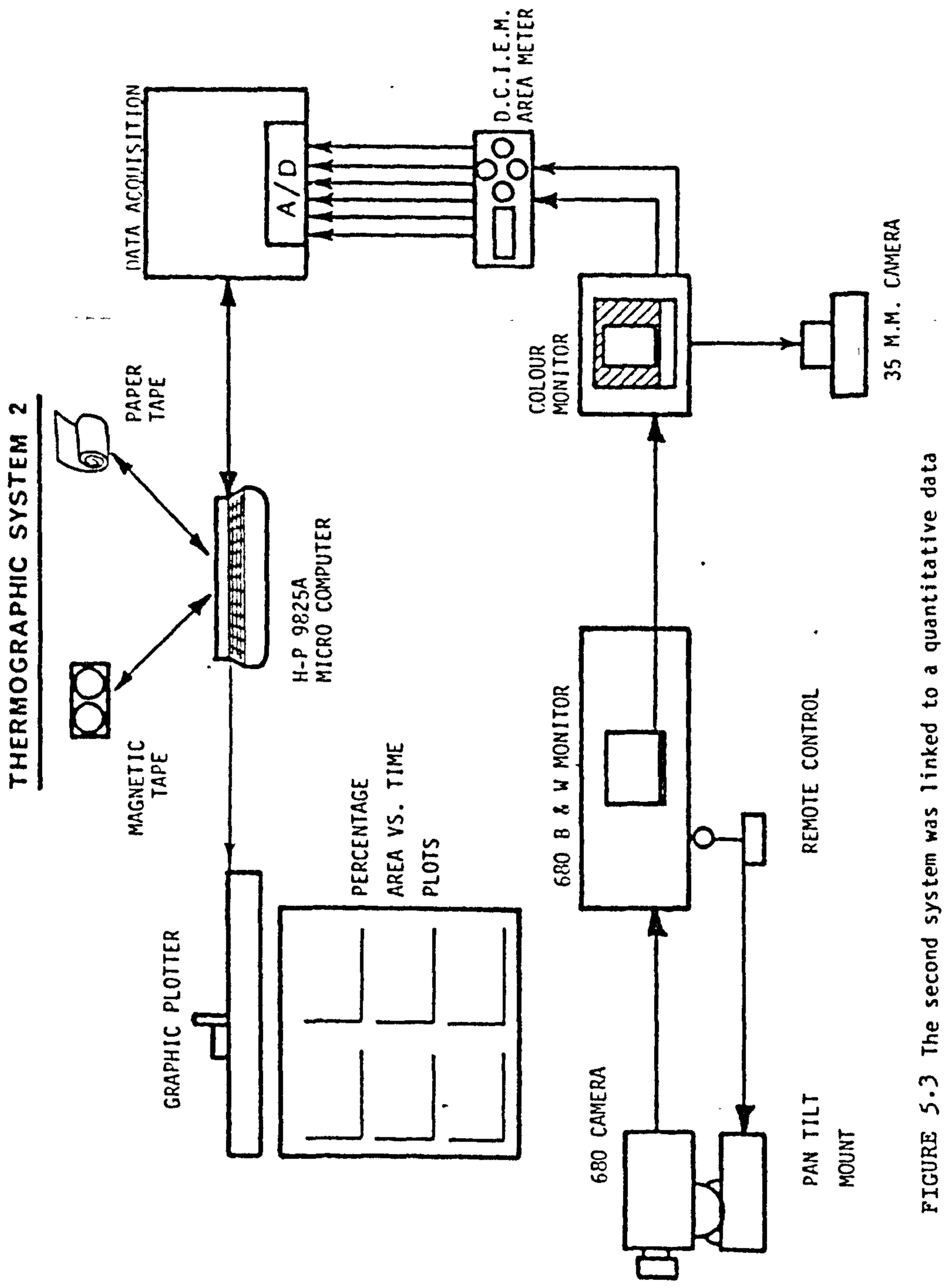


FIGURE 5.3 The second system was linked to a quantitative data gathering system

of 0.5C° per isotherm, it was found necessary to recalibrate during the run to keep all of the skin within the displayed temperature range.

The thermographic camera for system 2, being the closer to the subject, had a smaller field of view. Because it was not possible to have an absolute temperature reference in the picture at this range, a large copper constant temperature water bath was used, adjacent to the subject. The temperature of the bath was kept uniform by means of a thermistor controlled heater-stirrer and maximum energy radiation was accomplished by having a flat radiant surface painted matt black. When recalibration was necessary the camera was rotated by its pan-tilt attachment towards the large calibrator to provide a rapid temperature reference. However, when examinations were run at a sensitivity setting of 1C° per isotherm and the middle temperature level was set at 33°C, no recalibration was required.

5.1.4 Trials

Two sets of trials were conducted. In the first, tissue response to prior loading was studied by comparing each subject to himself on different seats, see Table 5.1. Two complete sets of these stress tests were run at an ambient temperature of 23.8°C, and an additional set at 18.3°C to form a comparison. A preliminary analysis at the end of this first series of tests, based on measurements of peak temperature, isotherm areas and on a review of the time-lapse movie films, indicated that the camera for system 2 should be positioned much more closely to the subject to decrease the total sampling window area from 50% to 30% of the screen.

TABLE 5.1 SUBJECT TRIALS

DISTRIBUTION BY SUBJECT AND AMBIENT TEMPERATURE

TRIAL SERIES I

	T_{amb} 18.3°C				T_{amb} 21.0°C				T_{amb} 23.8°C				T_{amb} 26.6°C			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
stress (III&III) (Plywood Base)									* 2	2	2	2				
stress (II&II) (Base & Foam)	1	1	1	1					* 2	2	2	2				
stress (IV&I) (Base cut out)	1	1	1	1					* 3	3	4	4				
stress (I&I) (No sitting)																

TRIAL SERIES II

stress (III&III) (Plywood Base)																
stress (II&II) (Base & Foam)	* 1	1	1	1												
stress (IV&I) (Base cut out)	* 1	1	1	1	* 1	1	1	1					* 1	1	1	1
stress (I&I) (No sitting)	1	1	1	1	1	1	1	1					1	1	1	1

In the first set of trials (I) several procedural problems were detected and modified for the second set of trials (II):

1) The quantitative "windows" were too large and the target area of stress too far away;
2) the need for an automatic switching system was identified (to bring the locating and changing of the "window" from one side to the other, under software control); and
3) the sensitivity was reduced to 1°C per isotherm to eliminate the need for recalibration and the noise this procedure introduced into the data.

Note: (*) indicates maximum temperature data from system 1 was available

The second set of trials made use of the asymmetrical stresses produced by the plywood base with cut-out. The asymmetrical sitting test (IV-I) was conducted at each of four ambient temperatures to determine the possible influence of changes in ambient temperatures on measured skin cooling. Baseline standing thermographs were also used to compare the cooling rates obtained in the various ambient temperatures.

5.1.5 Data Analysis

5.1.5.1 types of analyses

Two thermographic systems were used, each of which provided qualitative and quantitative data, see Table 5.2

TABLE 5.2 Data Formats

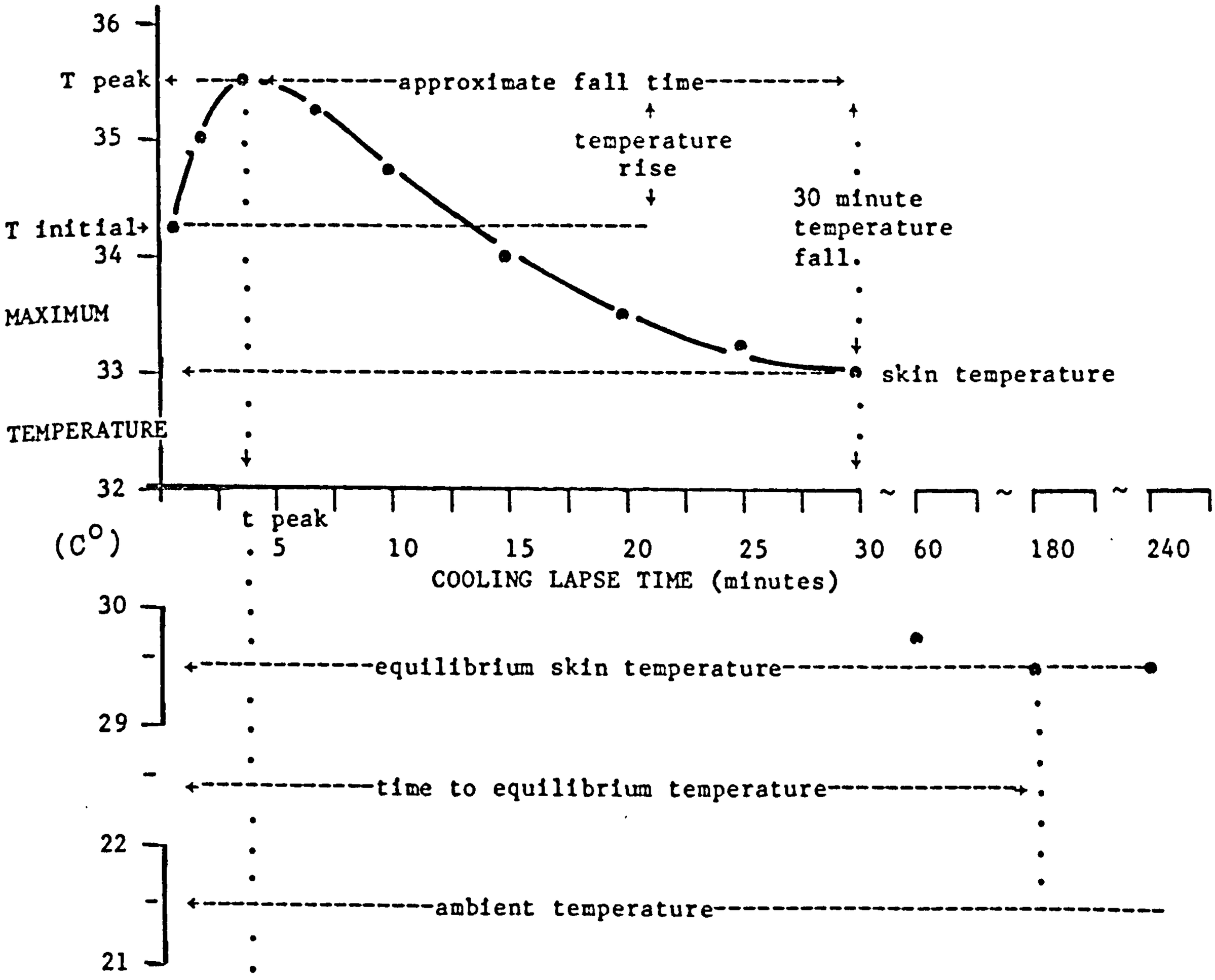
	Qualitative	Quantitative
System 1	cine films	maximum temp. vs time
System 2	35 mm slides areameter graphs	mean image temp. vs time

Although the visual thermographs contained quantifiable data they were used in this context as qualitative images.

5.1.5.2 maximum temperature analysis (system 1)

Maximum temperature graphs were plotted for the high stress sites (the ischial tuberosities), using the white isotherm marker on the black and white monitor of thermographic system 1. All of these had a similar shape, shown diagrammatically in Figure 5.4, which included an initial rise in temperature, followed by a cooling

FIGURE 5.4 THEORETICAL MAXIMUM SKIN TEMPERATURE RESPONSE TO ISCHAEMIA



trend. It was anticipated that this type of curve approached an equilibrium temperature, although the cooling time of 30 minutes, chosen for these experiments, was too short to demonstrate this phenomenon. For each graph, three discrete points were used to characterize each curve; the initial temperature (T_0), the peak temperature (T_{peak}), and the final temperature (T_{30}), after 30 minutes of cooling.

In instances of hyperthermic response, initial temperature changes were very rapid, so that it was often difficult to coordinate precisely the temperature readings, and the time intervals during the first minute. The points were subsequently curve fitted manually to provide interpolated points for data sampling at five minute intervals.

The following parameters were calculated to characterize the skin temperature response:

$(T_r = T_{peak} - T_0)$	temperature rise
$(t_r = t_{peak} - t_0)$	rise time
$(T_{fall} = T_{peak} - T_{30})$	temperature fall
$(t_{fall} = t_{peak} - t_{30})$	fall time

The experiments had three major parameters; subject, ambient temperature and sitting stress, with four options for each. As a result there were 64 possible experimental combinations of which 48 were used with one or two trials. For this reason, the statistical techniques available were limited to scatter graphs and comparisons of means with standard deviations.

Trends were detected by grouping data with one or two of the parameters in common (i.e. all of the data for one subject at a

common ambient temperature). The sample sizes under these restraints were typically 8 for one parameter and 4 for two.

5.1.5.3 mean imaged temperature data

The areameter automatically measured the areas of each isotherm as a percent of the total field of view of the thermograph. Several display modes were developed to facilitate perception of the systems sensitivity, see Table 5.3. In particular two modes were found to be useful in characterizing skin temperature response to prior loading. The unprocessed data was displayed by the accumulated percent area format and the hyperthermic responses emphasized by summing from the highest temperature range to the lowest, see Figure 5.5. The nine percent area versus time graphs in the top half of this figure present the raw areameter data with contralateral and difference plots superimposed.

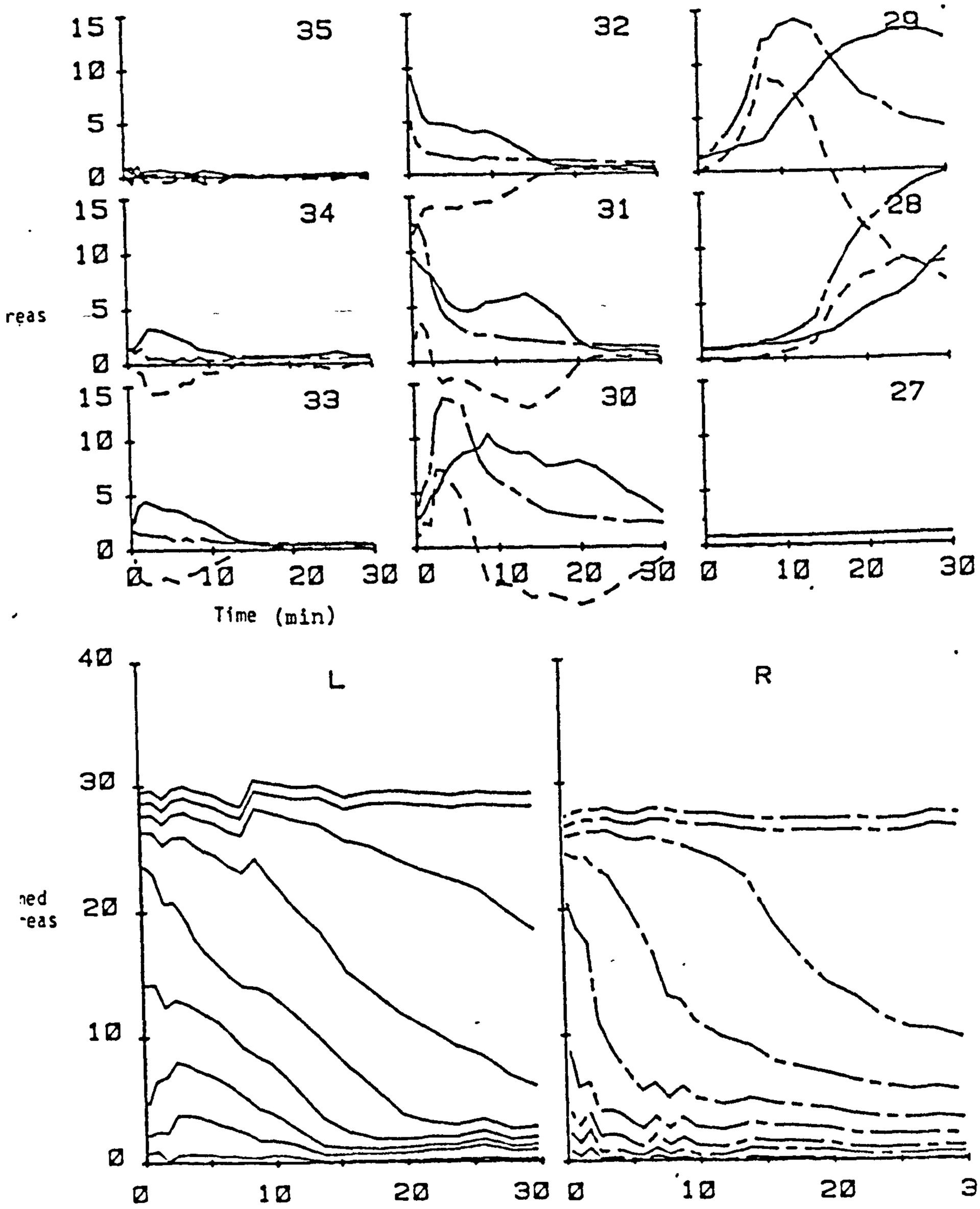
The sample case demonstrates the results of an asymmetrical prior loading (left-IV versus right-I). In individual channel displays the highest temperture response is seen in the 34°C temperature range peaking at 3 minutes. The same information is presented in the accumulated percent area plots immediately below. The content of each channel is summed from the highest to lowest isotherm range (33°C to 27°C) During the first 5 minutes of response the stressed side (L) has a family of concave down loci while the opposite pattern is seen on the contralateral unloaded side.

The mean imaged temperature versus time plots were used to quantitatively characterize the skin temperature response to prior loading, see Figure 5.6 . The parameters calculated from this normalized data are listed below:

TABLE 5.3 AREAMETER DISPLAY MODES

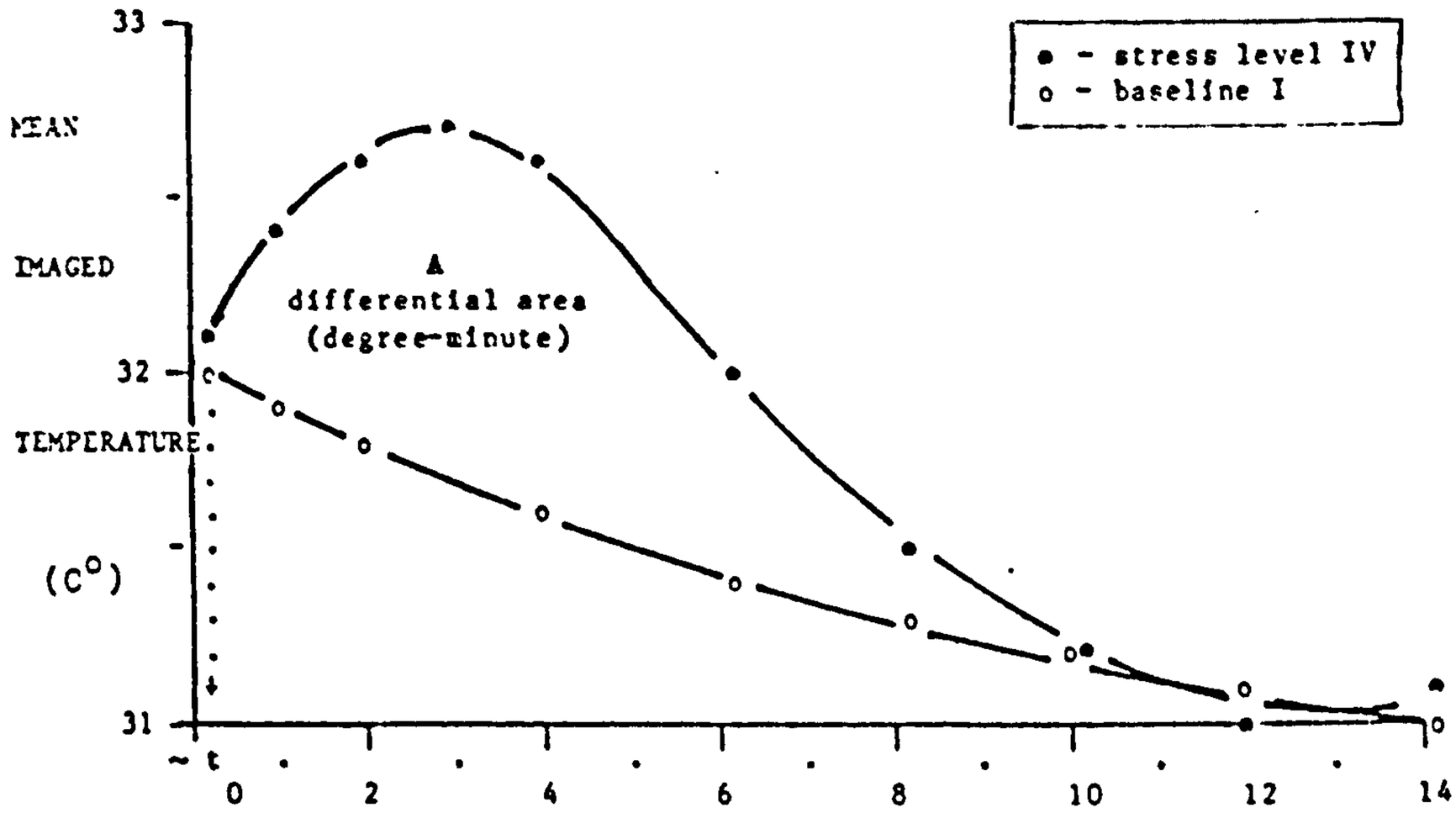
Display Mode	Example	Characteristics	Application
ISOTHERM (by channel)	Appendix I	- plot of percent area versus time - overlay of two window views and a difference plot - addition of pairs of adjacent channels to generate lower sensitivity plots (i.e. 1C° per channel and combined to show 2C° per channel)	- detection of temperature response within a narrow temperature range - direct comparison of contralateral assymmetry within a specific temperature range - display of raw data to identify discontinuities which might be due to system errors
ACCUMULATED PERCENT AREA (LOW TO HIGH)	Appendix I	- plot of summed percent area versus time - lowest temperature channel nearest the abcissa - total sum of all channels is constant (area of the window) represented by a line parallel to the abcissa	- demonstration of relative contributions within a temperature range at a given point in time - low to high temperature mode emphasizes cooling trends
ACCUMULATED PERCENT AREA (HIGH TO LOW)	Figure 5.4 Figure 5.5	- plot of summed percent area versus time - highest temperature channel is nearest the abcissa - sum of all channels is constant (size of the data window) - high temperature perturbations are accentuated	- display sensitive to hyperthermic changes in skin - detection of hyperaemia and inflammation
MEAN IMAGED TEMPERATURE LOCUS	Figure 5.6	- plot of mean temperature versus time - compression of data into a single locus - characteristic features such as initial, peak and final sample times - describe by curve fitting techniques	- compression of data for characterization - characterization of cooling response of skin after loading -

FIGURE 5.5 CHANNEL BY CHANNEL ISOTHERM AREA DATA AND ACCUMULATED PERCENT AREA VERSUS TIME

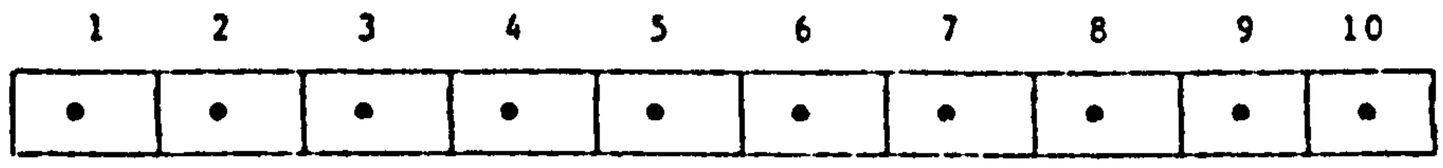


Upper: % Areas vs. Time, Stress Levels I and IV
Lower: Summed % Areas vs. Time
$T_{ambient} = 21^{o}C.$

FIGURE 5.6 MEAN IMAGED TEMPERATURE VERSUS TIME CHARACTERIZATION



MEAN IMAGED TEMPERATURE CALCULATION

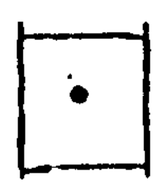


$$i = \overset{v}{T} \quad T_1 \quad T_2 \quad T_3 \quad T_4 \quad T_5 \quad T_6 \quad T_7 \quad T_8 \quad T_9 \quad T_{10}$$

$T_i = \overset{v}{T} + (i - \frac{1}{2})\, S$ channel temperature

$\bar{T} = \overset{v}{T} - \frac{S}{2} + \frac{S}{A} \Sigma\, i\, a_i$ mean temperature

a_i, denotes isotherm area for ith channel
A, window size ($A = \Sigma\, A_i$)



+ S +
(°C)
sensitivity

$\bar{T}_{(0,5,10,\ 15\ \&\ 20)}$ - the mean imaged temperature at five minute intervals (time "0" represented the first sampled temperature)

$\Delta\bar{T}$ - the difference between contralateral mean imaged temperatures at time (i) for symmetrical stresses, I, II and III:

$$\Delta\bar{T}_i = \bar{T}_{left} - \bar{T}_{right}$$ and for assymmetrical stresses IV / I

$$\Delta\bar{T}_i = \bar{T}_{IV} - \bar{T}_{I}$$

The mean temperature ($\bar{T}$) was calculated as follows:

$$T_i = \overset{v}{T} + (i-1)S + \frac{S}{2}$$

The temperature (T) representative of a given isotherm channel (i) was considered to be that in the middle of the range, which had a magnitude equal to the sensitivity (S). The lowest temperature ($\overset{v}{T}$) within the ten channel scale was added to by the appropriate number of isotherm intervals, see Figure 5.6 . The expression simplifies to:

$$T_i = \overset{v}{T} + (i-\frac{1}{2})S$$

The mean temperature ($\bar{T}$) was then calculated from a division of the summed area-temperature product ($\Sigma a_i T_i$) by the total area (Σa_i):

$$\bar{T} = \frac{\Sigma a_i T_i}{\Sigma a_i}$$

if $A = \Sigma a_i$, then by substitution:

$$\bar{T}\ A = \sum_{i=1}^{10} a_i \left(\overset{v}{T} + iS - \frac{S}{2}\right)$$

$$= \frac{Y}{T}\Sigma a + S\,\Sigma i a_i - \frac{S}{2}\Sigma a_i$$

$$= \frac{Y}{T}A + S\,\Sigma i a_i - \frac{SA}{2}$$

$$= A\left(\frac{Y}{T} - \frac{S}{2}\right) + S\,\Sigma i a$$

therefore:

$$\bar{T} = \frac{Y}{T} - \frac{S}{2} + \frac{S}{A}\Sigma i a_i$$

$\Delta \int_{i=0}^{10} \bar{T}dt$ - the difference in area under the mean imaged temperature versus time plots was with a mechanical planimeter using regimen of (left - right or measured stress IV - stress I)

In addition, mean temperature changes were calculated for the time intervals (0-5, 5-10 and 0-20 minutes) for each side.

5.2 RESULTS

5.2.1 Visual Thermographic Data

5.2.1.1 cine films (system 1)

The review experiments using the various stresses, I through IV, demonstrated the presence of a hyperthermic response, peaking within the first three or four minutes after sitting. Two basic types of response to the range of stresses were encountered in the experimental seats. The lesser stresses,(ie. those not associated with the relatively high pressures over the ischial tuberosities),

produced skin temperatures which were at a maximum level immediately after sitting and decreased subsequently throughout the 30-minute observation time. Greater pressures, such as those induced by stress levels III and IV over the bony prominences, resulted in skin temperatures which increased for the first three or four minutes of observation before cooling. In addition, those patterns of temperature seen to develop during the first few minutes remained evident throughout most of the examination period, in spite of the overall drop in skin temperature. Visually, the areas of localized high temperature were readily apparent in the colour monitor display, although the area of highest temperature was typically very small, approximately 5% of the field of view.

Problems were encountered in the visual interpretation of the cine film when recalibration was required because of the resultant colour shifts. Consequently, sensitivity was decreased from 0.5 to 1C° per isotherm in the second set of trials. This resulted in a continuous display of the entire cooling process throughout the 30 minute period.

5.2.1.2 35mm slides (system 2)

Colour thermographs were interpreted by reviewing the images in conjunction with the quantitative data. A sample series of these slides, taken at moments of particular interest, is seen in Figure 5.7. These thermographs represent a typical series of sitting trials for subject A, comparing skin temperature responses to all the test seats . Viewing one of these thermographs in more detail (for example, the one minute slide for the bottom row), the following landmarks are clear:

FIGURE 5.7
CONTROLLED ENVIRONMENTAL STUDIES
(SUBJECT A; SEATING COMPARISON)

CONTROLLED ENVIRONMENT STUDIES

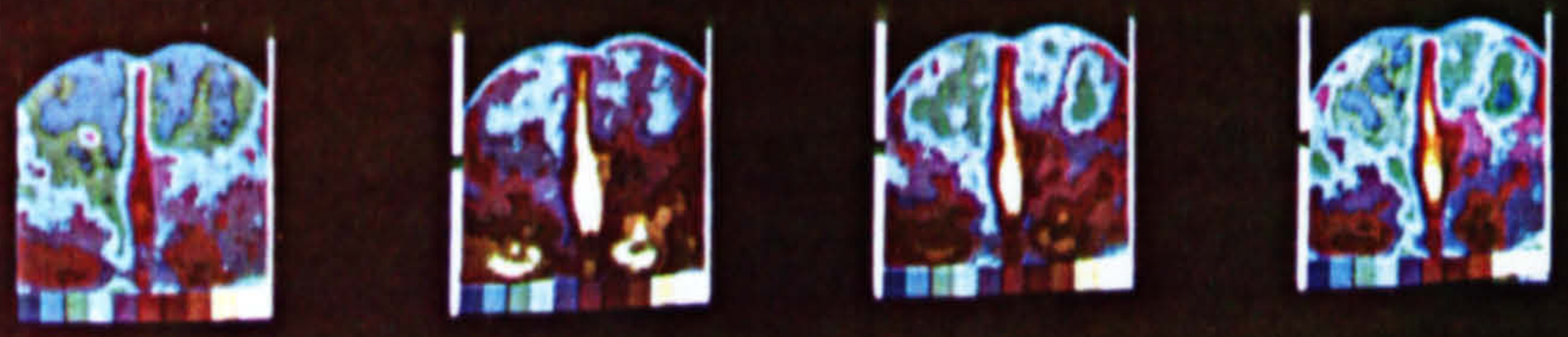
AMBIENT CONDITIONS: TEMPERATURE 75°
HUMIDITY 40%
DRAFT 0 F.P.S.

TRIALS: ½ Hour Sitting On Indicated Surface

SURFACES

Plywood Base

Plywood Base And Foam



Plywood Base With ¼ Cut Out Of Back

(Cooling Times) 1min. 3min. 15min. 30 min.

SUBJECT A

1. A colour scale (white hot, blue cold) is visible at the base of the thermograph.
2. The scale is divided into ten colours (isotherms).
3. A notch on the left hand border marks the sensitivity of the system (0.5°C per isotherm in this case).
4. A "white" hot vertical line in the middle of the field of view, highlights the gluteal cleft, which always appears warm because of the highly vascularized perineal tissues and the reflective geometry of the gluteal masses.
5. Red areas in both bottom corners of the thermograph correspond to the proximal surface of each thigh.
6. The yellow region in the top left corner of the field of view represents the stressed tissue overlying the ischial tuberosity.

In viewing the other thermographs, several factors must be considered. As mentioned in the results of system 1, at this sensitivity of 0.5C° per isotherm, recalibration was required prior to 3 and 15 minutes to keep all of the recordings within the detected temperature range. Consequently in Figure 5.7, row 2, the entire surface area for the one minute thermograph appears cooler than in the pictures taken at 3 and 15 minutes.

The results of both the cine and the still pictures reinforced the value of reviewing these colour images sequentially. Initial, qualitative views can be used to identify sites of risk and to obtain a general impression of the overall weightbearing pattern for the buttocks.

5.2.2 Influence of Prior Loading on Skin Temperature

5.2.2.1 maximum temperature response (system 1)

The data were grouped by stress levels combining both subjects and ambient temperatures. The sample variability was comparable for the three plots, stresses II, III and IV, at approximately ± 1.0 C°, see Figure 5.6. The absolute peak temperature did not appear to be strongly dependent upon the experimental changes in sitting stress, as all fell within ± 1.0 C° of 35.5 °C. The cooling trends were described in terms of the temperature drop during the first 30 minutes as follows in Table 5.4 below:

Table 5.4 Influence of Prior Loading on Maximum Temperature Decay

STRESS LEVEL	$T_0 - T_{30}$°	± 1 σ
II	- 4.3	0.7
III	- 5.3	0.8
IV	- 2.9	1.0

There was a greater drop in skin temperature for the symmetrical stress levels III and II than for level IV and also a significantly smaller temperature change after the peak temperature for stress level IV. This indicated that both the magnitude of the peak temperature and the subsequent cooling rate were required to describe the overall skin temperature response to stress. The hyperthermia, resulting from the highest stress level, appeared to delay the cooling process, although the average peak temperature was not significantly greater than that for stress level III.

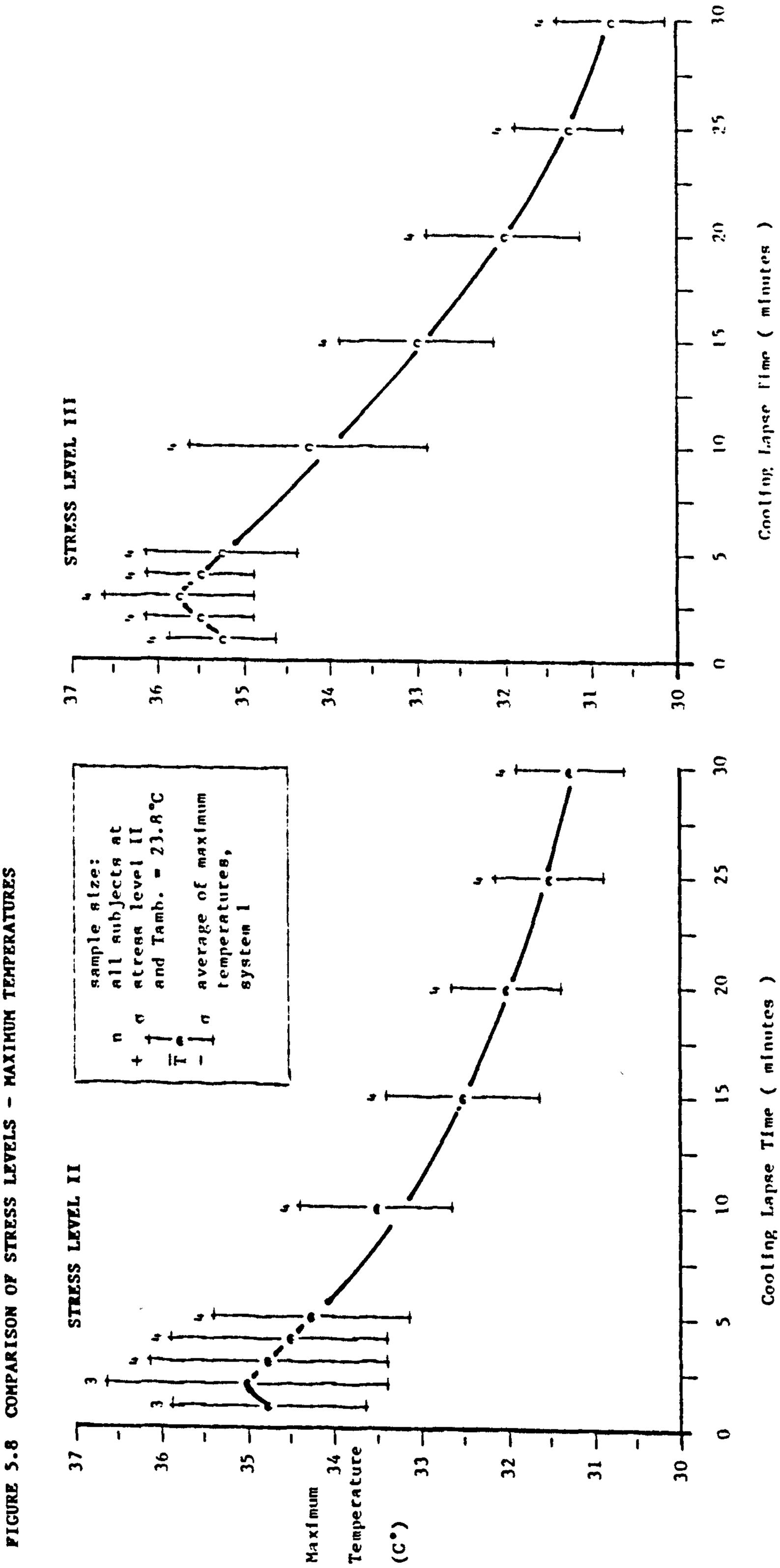
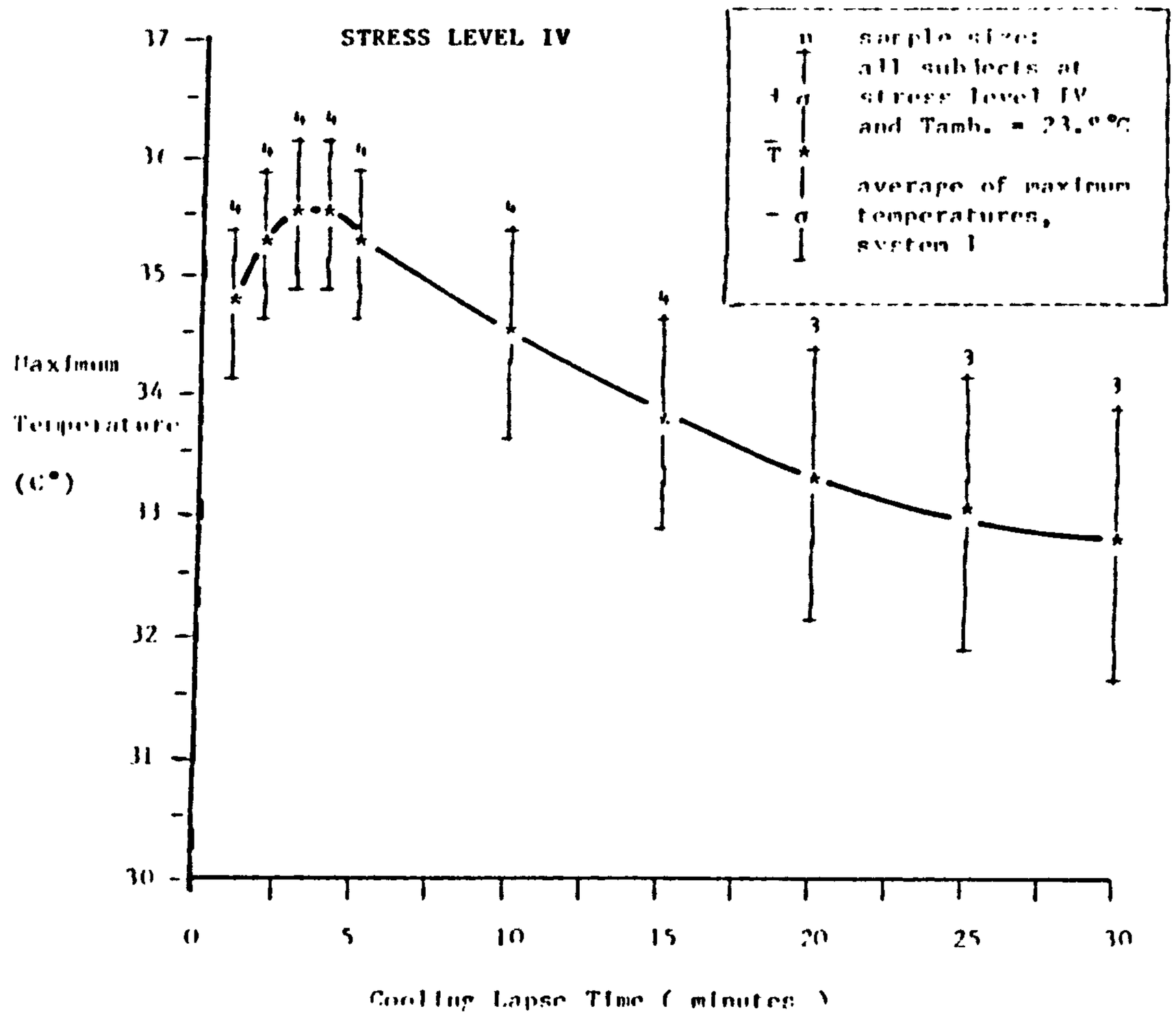

COMPARISON OF STRESS LEVELS - MAXIMUM TEMPERATURES
STRESS LEVEL III
STRESS LEVEL II
sample size:
n all subjects at
+ σ stress level II
and Tamb. = 23.8°C
T̄
- σ average of maximum
temperatures,
system 1
Maximum Temperature (C°)
Cooling Lapse Time (minutes)
37
36
35
34
33
32
31
30
0
5
10
15
20
25
30

FIGURE 5.8

FIGURE 5.8 COMPARISON OF STRESS LEVELS - MAXIMUM TEMPERATURES



The temperature rise, and the rise time, were compared for various test conditions by plotting them as coordinates with their respective standard errors defining areas of probable occurrence, see Figure 5.9. Two trends were readily observed; the variability decreased as the stress increased (i.e., smaller rectangles) and neither the temperature rise nor the rise time were significantly different between test groups by this measure. On the basis of these data the pressure induced ischaemia may have reached some maximum or saturation level for all the seating systems.

5.2.2.2 mean imaged temperature comparison (system 2)

The mean temperature data were used to compare contralateral responses by plotting loci of the means and by calculating the means of the contralateral differences for the following samples:

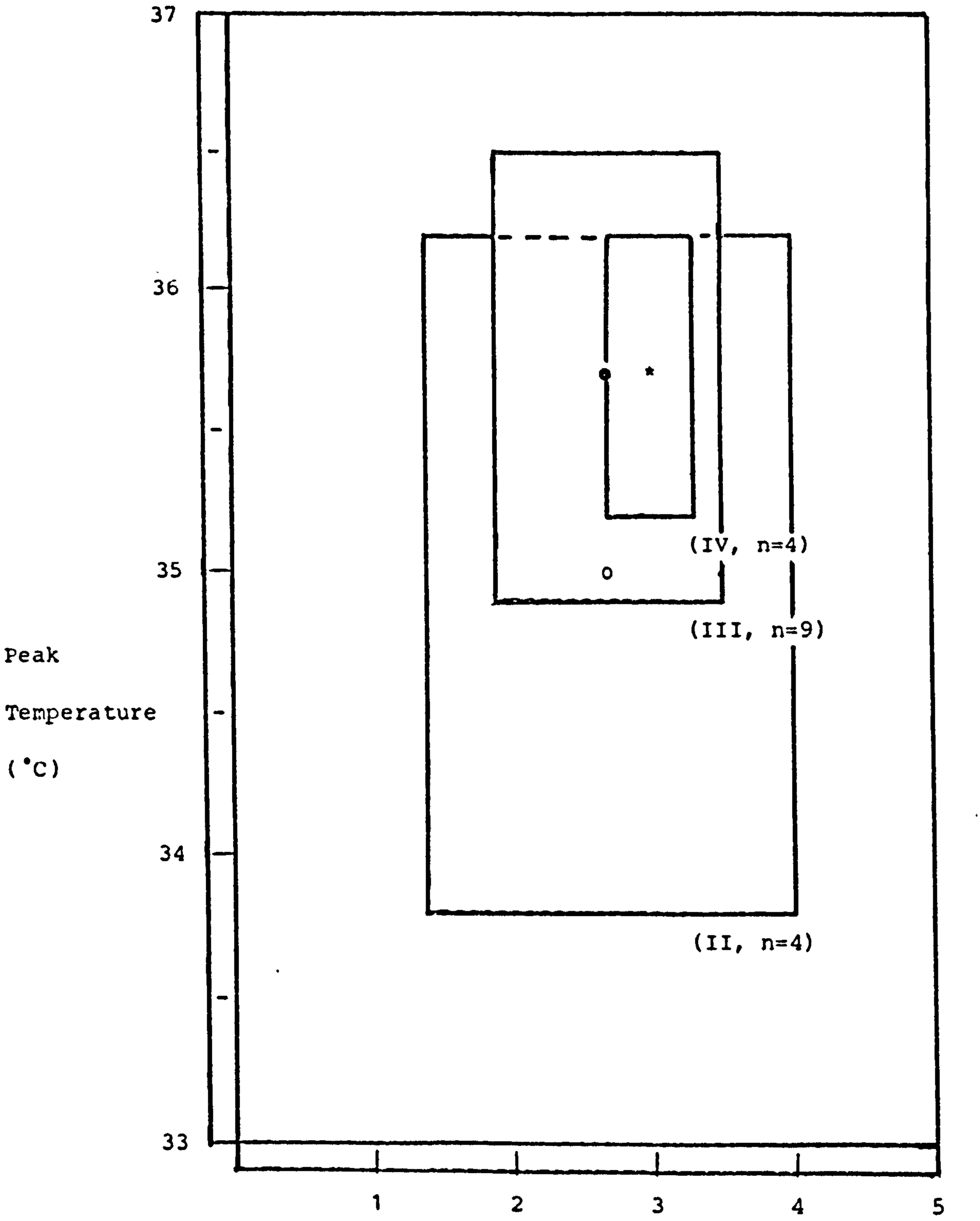
i) all samples for symmetrical stresses (I_l- I_r, II_l- II_r and III_l-III_r);

ii)symmetrical stresses (II_l- II_r and III_l- III_r) at the ambient temperature of 23.8 C°; and

iii)asymmetrical stresses (IV-I) for individual and combined ambient temperatures

The differences of calculated means were considered significant if the ratios of the mean to one standard deviation of the mean was greater than 1. Stress sensitivity was found in two of the parameters, the difference in mean imaged temperatures ($\Delta\bar{T}_{0 \text{ and } 5}$) and the differencs in areas under the mean imaged temperature curves ($\Delta\int_0^{10} Tdt$). Comparing all of the tested combinations for symmetrical stress tests 2 of 30 had a significant difference; whereas, 8 of 30 asymmetrical tests were significant.

FIGURE 5.9 INFLUENCE OF PREVIOUS LOADING ON PEAK SKIN TEMPERATURE RESPONSE



The cooling ratios for contralateral sites at specified time intervals were found to be negative for stress combination (IV - I), see Table 5.5. One explanation of this result is that the stress induced a thermal response in the skin which counteracted atmospheric cooling as represented by stress I.

Averaged mean imaged temperature versus time curves were plotted by manually interpolating between five minute intervals. The stress responses were compared by combining the data from all subjects for the ambient temperature 23.8°C, see Figure 5.10.

The variability was approximately the same for all the stress plots (± 0.5 C°) with initial temperatures ranging from 32.8 - 33.8 °C. Temperature drop during the 20 minute sample period was (I-1.7C°, II-2.3C°, III-1.5C° and IV-1.7C°). These tests were all conducted with areameter windows totalling 50% of the screen size and hence having a low sensitivity to localized temperature changes. It was not suprising therefore to find no significant differences between loaded and unloaded sites. However, subsequent tests, comparing the stress level IV with standing baseline data (IV - I), did record local increases in temperature on the loaded side during the first few minutes when the smaller 30% data window was used.

5.2.3 Variability of Quantitative Data

5.2.3.1 observer influence on maximum temperature data (system 1)

The distribution of observers, subjects and experimental conditions is shown in Figure 5.11a . Since the number of tests for each combination of the above parameters was small the observers are indicated by code number on each of the subsequent graphs.

TABLE 5.5 RATIO TEST FOR THE INFLUENCE OF AMBIENT TEMPERATURE ON MEAN IMAGED SKIN TEMPERATURE

TEST PARAMETERS	RATIO OF MEANS TO THE STANDARD DEVIATION OF THE MEAN Ambient Temperatures			
	18.3 C°	21.0 C°	23.8 C°	26.6 C°
Contralateral Temperature Difference				
ΔT_0	1.3	0.2	0.5	1.1
ΔT_5	0.6	0.6	1.6	1.9
Contralateral Cooling Differences				
ΔT_{0-5}	-0.7	-0.5	-0.2	-1.7
ΔT_{5-10}	0.0	0.0	0.8	0.6
ΔT_{0-20}	0.6	-0.1	0.0	-2.5
Differential Temperature-Time Areas				
$\Delta \int_0^{10} T\, dt$	0.8	1.0	1.6	1.4
Number of Trials				
n	8	4	7	4

Interpretation:

For each parameter the data were grouped and averaged to calculate means and standard deviations. Ratios of the mean value to the standard deviation were used to identify sensitive parameters to tissue loading.

No ratios greater than 1 were found for symmetrical stress comparisons except for two occasions; a) ΔT_0 for stresses III_L- III_R (ratio = -2.0) and b) ΔT_{0-5} for baselines I_L- I_R (ratio = 1.3). In both of these tests the data were grouped for inclusion of all subjects at all ambient temperatures.

FIGURE 5.10 COMPARISON OF STRESS LEVELS - MEAN IMAGED TEMPERATURES

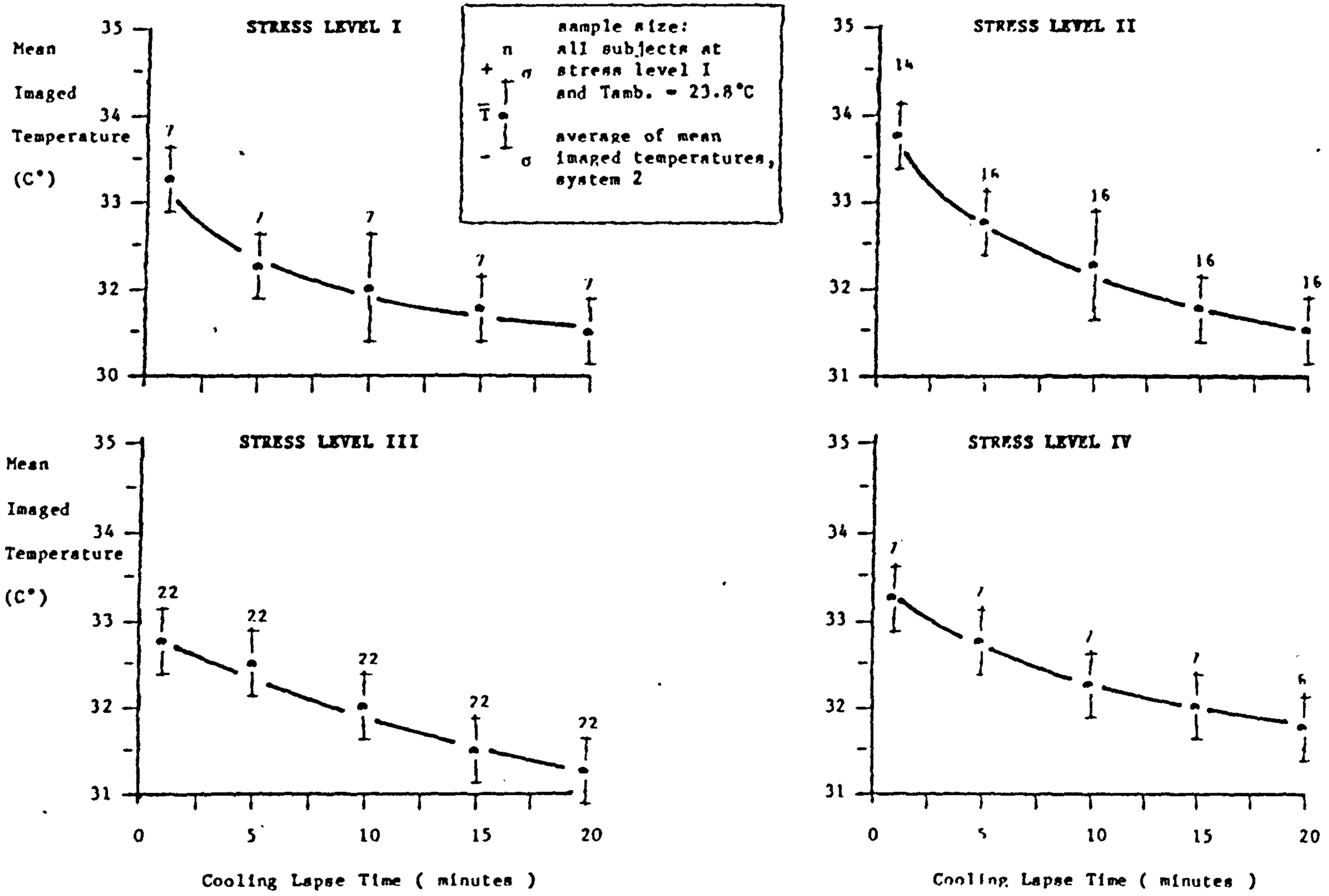


FIGURE 5.11a MAXIMUM TEMPERATURE DATA SOURCES

EXPERIMENTAL SUBJECTS

AMBIENT TEMPERATURE	A			B			C			D			OBSERVER CODES
18.3							1						1
									1	1			2
	1		1	1		2						2	3
			1						1				4
21.0												1	1
													2
													3
			1			1			1				4
23.8				1	2	1		2			1		1
	1	2	1						1		2	1	2
										1	1		3
							1						4
26.6									1			1	1
													2
						1							3
			1										4
	II	III	IV	II	III	IV	II	III	IV	II	III	IV	

STRESS LEVELS

n	Frequency of Observations

During one trial simultaneous readings were made by two observers to provide a direct comparison of recording techniques, observers #1 and #2 for subject D, see Figure 5.11b. The differences in observed temperatures between recorders during the first 20 minutes was 1C° and then decreased sharply after 20 minutes of cooling. This suggested that each observer was consistent in technique but that the criteria for ascertaining the maximum temperature differed. As the thermal patterns became more diffuse the consistency of the observation technique decreased.

The peak temperatures were considered the most reliable measure as only a small area of tissue was elevated in temperature. To estimate the magnitude of observer variation peak temperature averages were compared, see Figure 5.11c . The averages for observers #1, #2, and #3 were 35.2 °C ± (0.6, 1.0 and 1.1) respectively. Observer #4 had fewer recordings and an average of 34.6 °C ± 0.6 C°. This finding suggests that the difference noted between observers #1 and #2 was the greatest; however, such absolute temperature shifts due to observer technique would be within 1°C and could be compensated for by plotting temperatures relative to the peak temperature.

5.2.2.2 intrasubject variability (system 1)

Two sets of maximum temperature versus time graphs were used to determine the intrasubject variability. In Figure 5.12 duplicate recordings were obtained for each subject for stress level IV at an ambient temperature of 18.3 C°. All the readings for subjects B and D were made by observer #3, including both the minimum and the maximum variability. Differences in plots were summarized by averaging the differences for each time interval, see Table 5.6 .

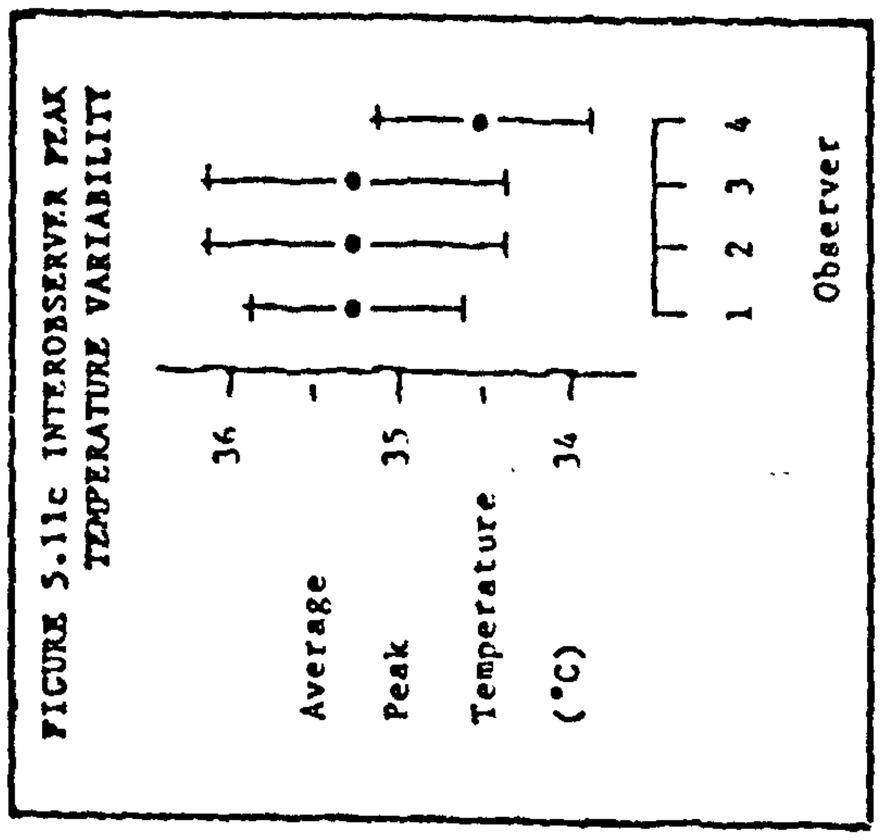


FIGURE 5.11c INTEROBSERVER PEAK TEMPERATURE VARIABILITY

FIGURE 5.11b INFLUENCE OF THE OBSERVER ON MAXIMUM TEMPERATURE DATA

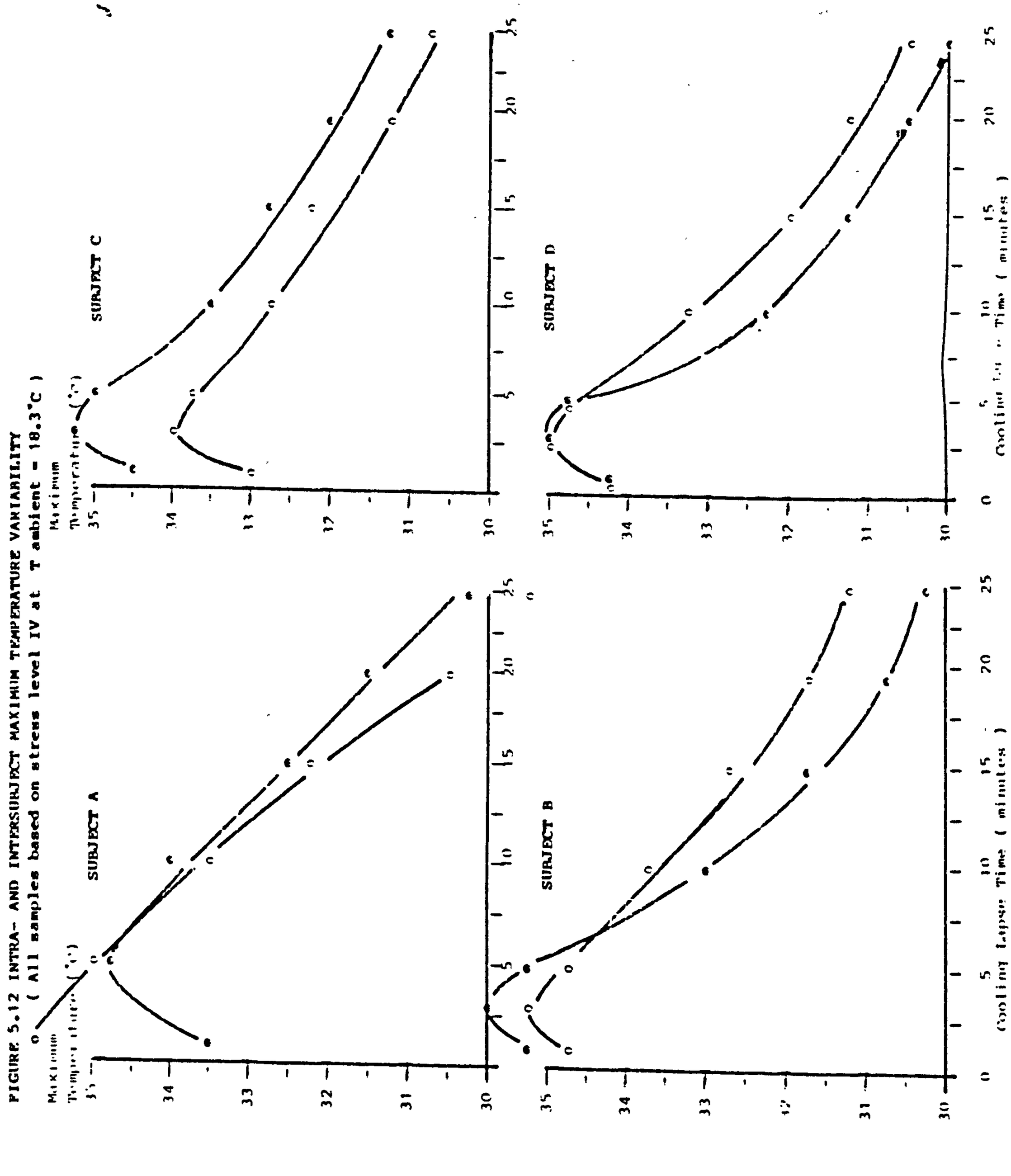


FIGURE 5.12 INTRA- AND INTERSUBJECT MAXIMUM TEMPERATURE VARIABILITY
(All samples based on stress level IV at T ambient = 18.3°C)

TABLE 5.6 Intrasubject Maximum Temperature Variability

Subjects	A	B	C	D
Observers	#4 & #3	#3 & #3	#2 & #4	#3 & #3
Averaged ΔT	0.6	0.7	1.0	0.2
1 σ	0.3	0.3	0.3	0.2
no. samples	10	10	10	10

The average maximum temperature plot for all subjects combined was superimposed on each subject's graph to provide a basis for intersubject comparisons. For all subjects either one or both of the sample plots fell within 1 standard deviation (σ) of the combined average. No subject differed significantly in response to severe loading conditions as measured by maximum skin temperature.

5.2.2.3 intra- and intersubject mean imaged temperature variability system 2

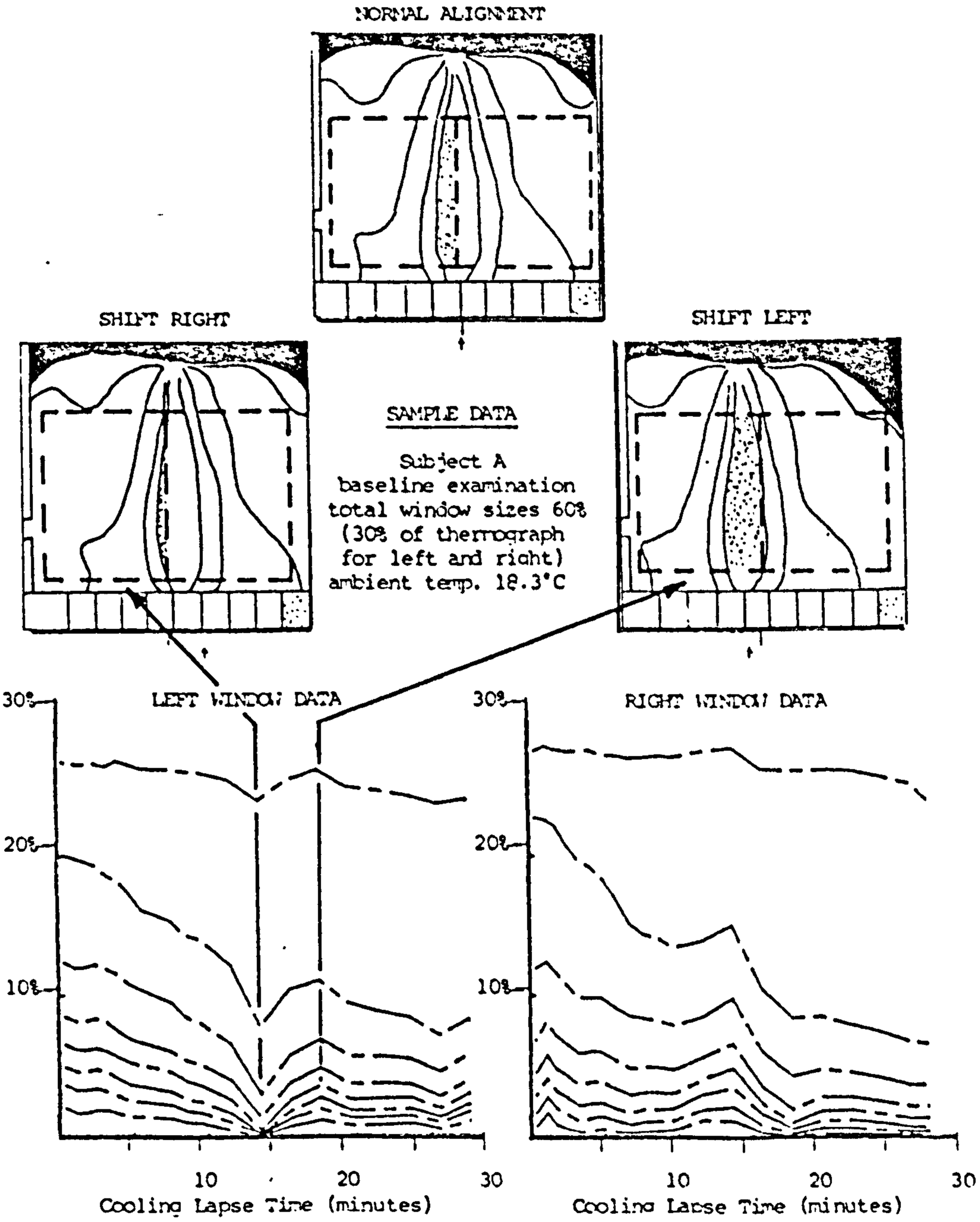
The data collection for system 2 was automated, thus limiting observer error to centering the field of view of the remotely controlled camera. Contralateral data sampling windows were used, such that tissues over the ischial tuberosities and the perineum contributed to the quantitative data. If the windows were misaligned or if the subject moved, one data channel would indicate higher average temperatures and the opposite would appear to cool simultaneously. The inverse accumulated percentage area data for a baseline examination at an ambient temperature of 18.3°C

demonstrates this effect, see Figure 5.13. At approximately 13 minutes the subject shifted to the right, causing an inverted peak in the data from the left sampling window and an increase on the right. Five minutes later, a small shift occurred in the opposite direction with the peaks and depressions reversed. The same operator was used throughout all tests to reduce the risk of operator error and 35mm slides were used to provide a visual record of the window position.

The intrasubject variability was estimated from comparisons of each subject with repeat examinations under the same test conditions, see Figure 5.14. For subjects A, B and D, the curve fitted mean imaged temperatures differed by less than 0.5°C. The greatest difference was observed with subject C, parallel cooling curves separated by an mean temperature difference of 1 C°. In a second comparison the average temperature differences for each sample time were averaged to derive an overall measure of intrasubject variability. A comparison, of all subjects demonstrated a variability ranging from 1.0 - 1.5 C°.

The intersubject variability may be described in terms of differences noted between the subjects from the previous Figures 5.14. For the single test condition, the cooling curves were similar in shape, having initial temperature ranges extrapolated between 32 - 33C°. For subjects A,B and D, average skin temperature cooled 3°C while only 1.5 and 2.0 C° for subject C during the 20 minute sample time. All of these curves fell within a range of ± 1 C° indicating that there was no evidence of significant differences in subject response.

FIGURE 5.13 EFFECT OF SUBJECT SHIFTING ON AREAMETER DATA



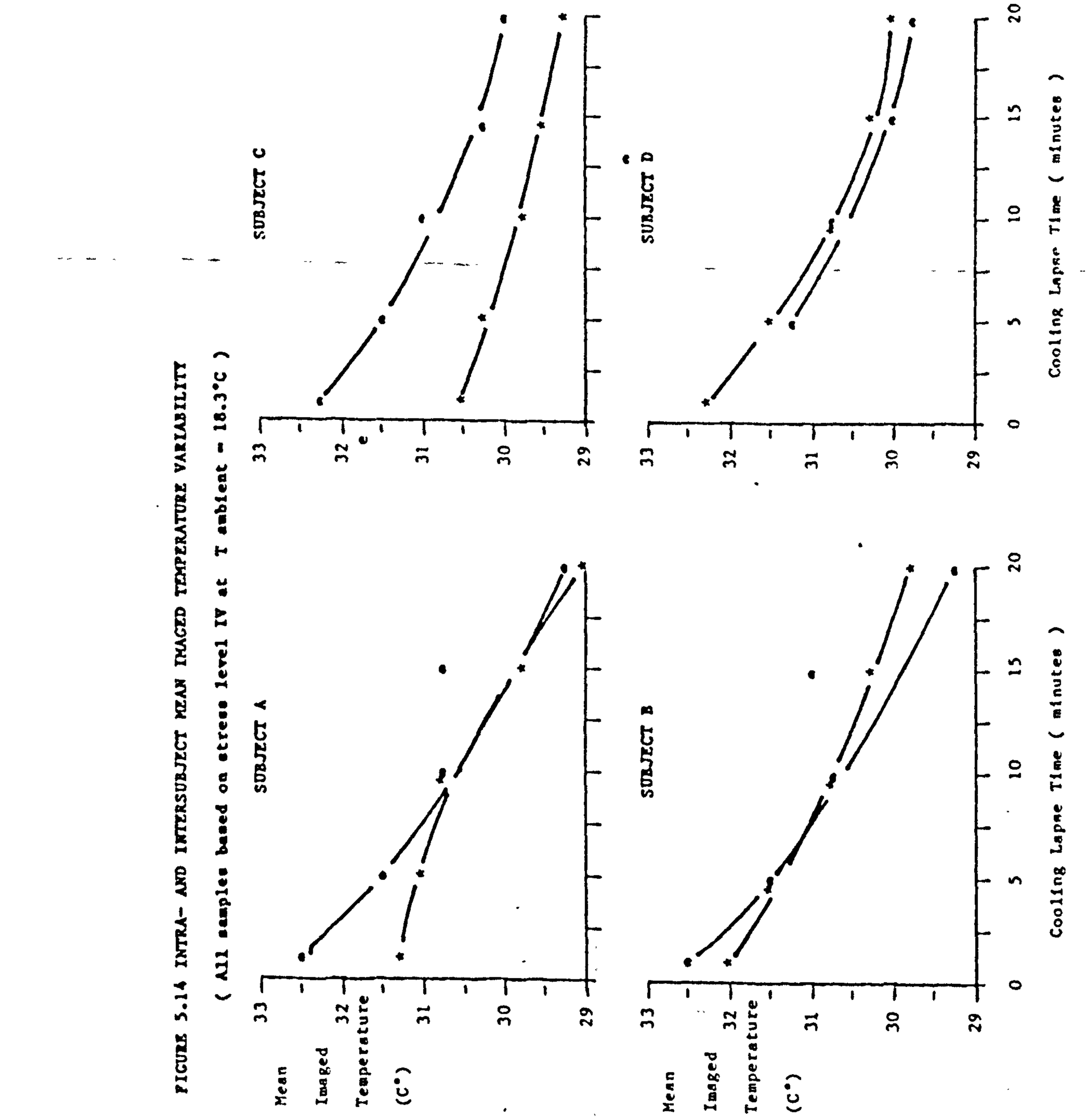


FIGURE 5.14 INTRA- AND INTERSUBJECT MEAN IMAGED TEMPERATURE VARIABILITY
(All samples based on stress level IV at T ambient = 18.3°C)

5.2.4 Influence of Ambient Temperature on Skin Temperature

5.2.4.1 maximum temperature response (system 1)

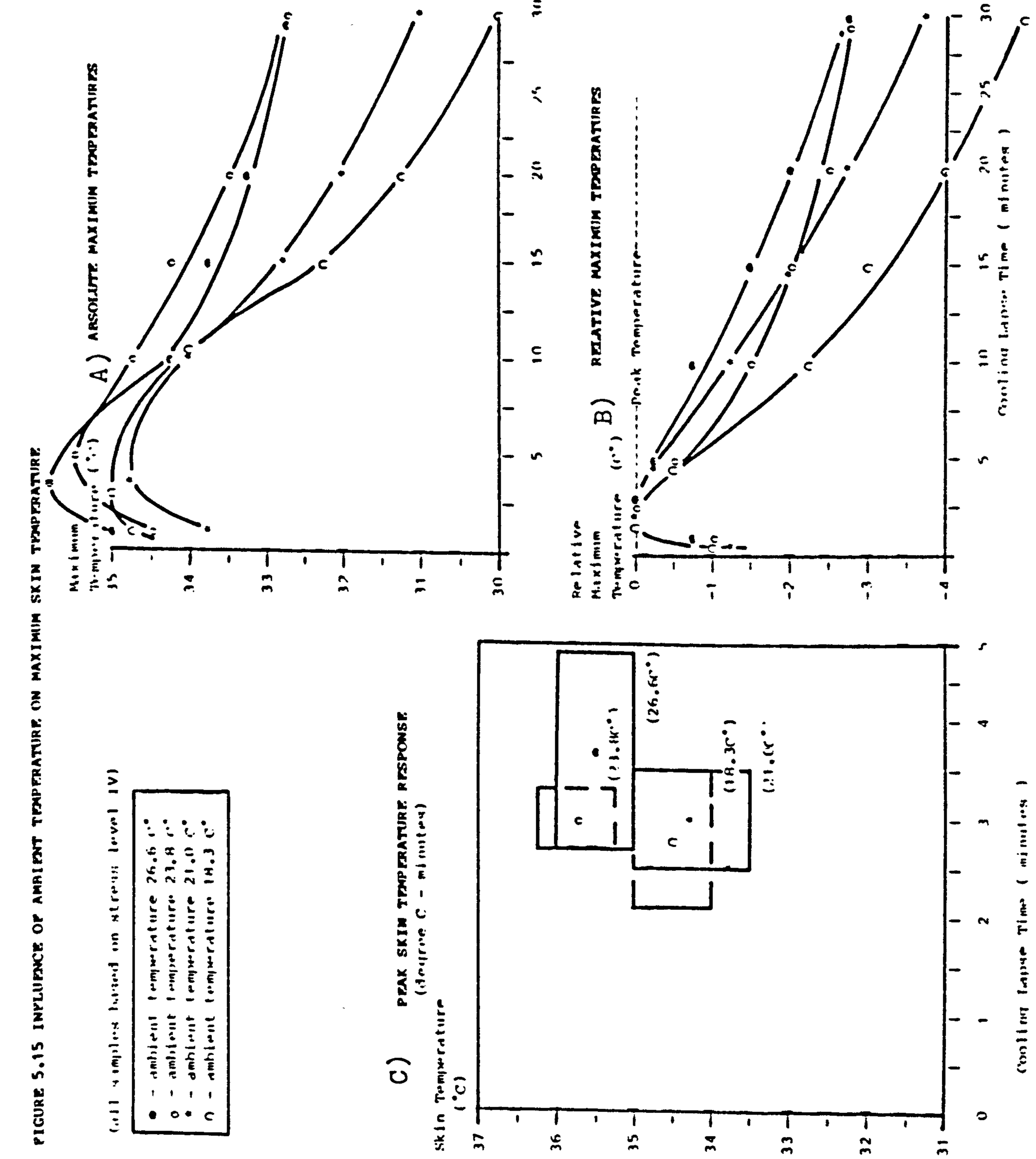
The data for all subjetcs were combined to generate averaged maximum temperature loci for each ambient temperature. The data sets included only stress level IV. Three maximum temperature versus time plots were used, see Figure 5.15, absolute (A), temperature relative to the peak temperature (B) and peak temperature versus peak time (C).

In all three graphs the higher ambient temperatures (23.8 and 26.6 °C) resulted in slower cooling rates and higher peak temperatures. In addition, the duration of the peak temperature was greater for the highest ambient temperature.

The significance of these trends can only be approximated because of the small sample sizes. However, the separation of cooling curves only appears to be greater than 1 standard deviation after 15 minutes of cooling for both absolute and relative temperatures, see Table 5.7 and the peak temperature difference for the two groups is about 1 standard deviation.

TABLE 5.7 Maximum Cooling

ambient temperature (°C)	relative temperature drop (C° ± 1 σ)
18.3	-5.1 ± 0.8
21.0	-4.8 ± 0.7
23.8	-2.9 ± 1.1
26.6	-2.8 ± 0.3



(All samples based on stream level IV)

● - ambient temperature	26.6 C°
o - ambient temperature	23.8 C°
• - ambient temperature	21.0 C°
○ - ambient temperature	18.3 C°

FIGURE 5.15 INFLUENCE OF AMBIENT TEMPERATURE ON MAXIMUM SKIN TEMPERATURE

5.2.4.2 mean imaged temperature sensitivity (system 2)

Samples of mean imaged temperature data were available for ambient temperature comparisons using standing baseline and stress level IV examinations. In Figure 5.16, plots of averaged mean imaged temperature versus time were calculated for groupings of all subjects by ambient temperature. There was no standing baseline data available for the data sampled in the 23.8°C ambient temperature sample.

Hyperthermic responses were only detected at the highest ambient temperature, 26.6 °C although the thermographs and maximum temperature data indicated transient hyperthermic responses for stress level IV at all ambient temperatures. The mean temperature display is not as sensitive to localized skin temperature fluctuations unless the data window is limited to the area of interest. In these experiments the inclusion of the perineal tissue introduced high temperature responses not related to the stress response under study.

The baseline only appeared to differ significantly from the stress response at the 26.6 °C data. The initial temperatures for the lowest ambient temperature may reflect the heat build up during sitting.

A further comparison was based on the areas measured between the mean temperature curves for stress level IV versus the contralateral no load stress. In Figure 5.17, these measures of asymmetry in average temperatures were compared with the same asymmetry test for corresponding baselines. The mean values were plotted within rectangles defined by the corresponding standard deviations. If there were no thermal asymmetry for the baseline (left minus right), the rectangles would overlapp the Y-axis.

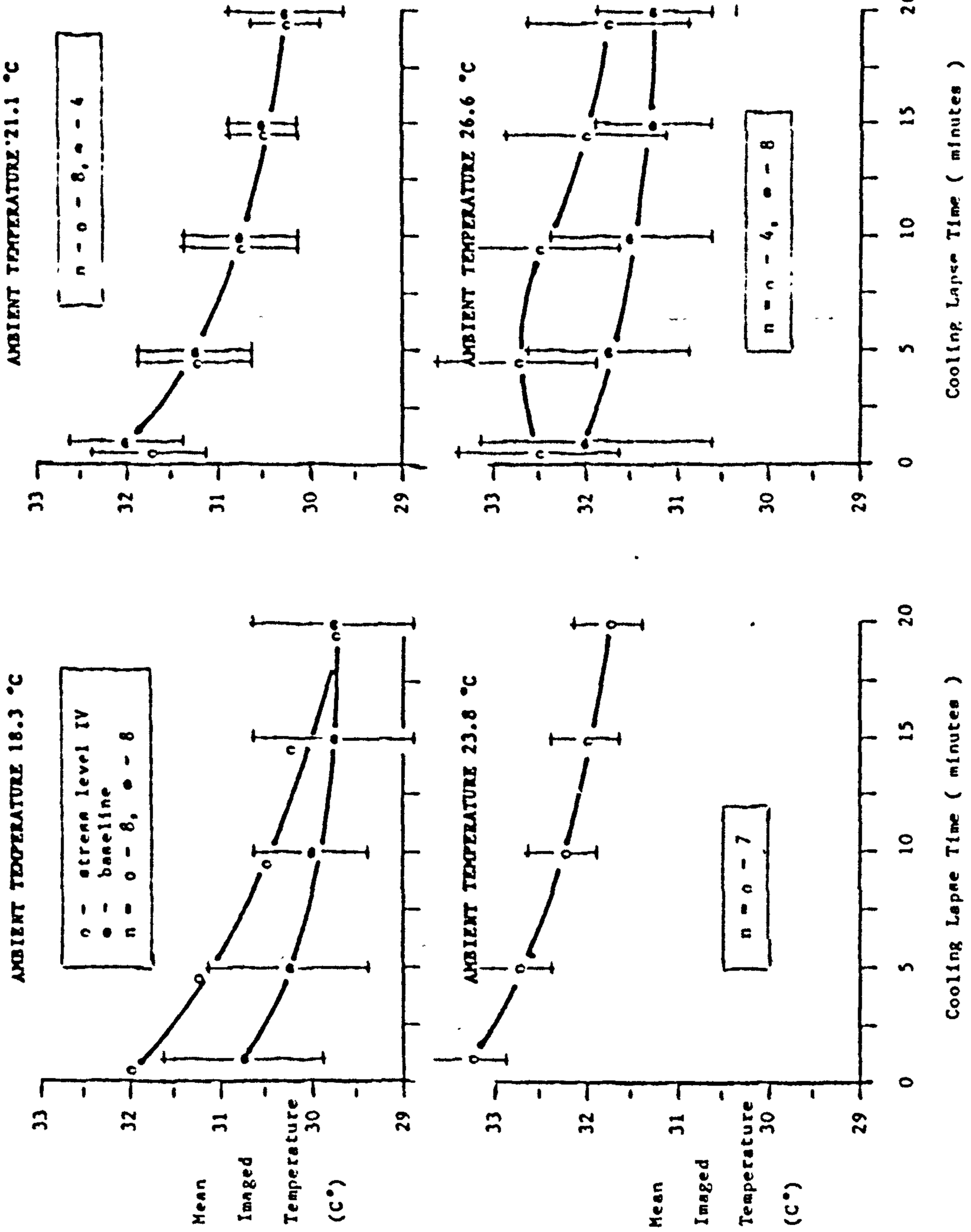
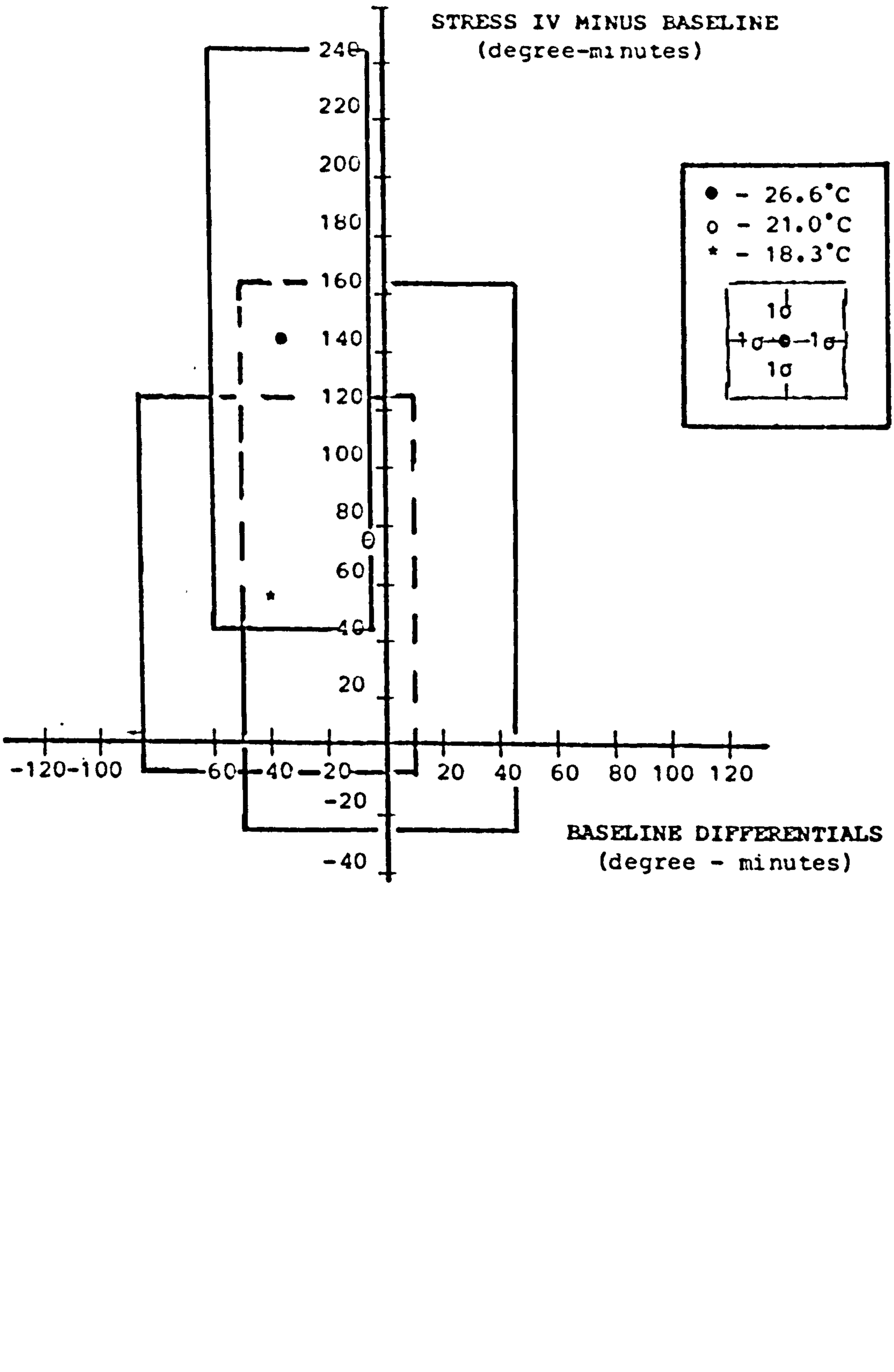


FIGURE 5.16 INFLUENCE OF AMBIENT TEMPERATURE ON MEAN IMAGED TEMPERATURES

FIGURE 5.17 INFLUENCE OF AMBIENT TEMPERATURE ON THE DIFFERENTIAL RESPONSE TO ASSYMETRICAL STRESS



Similarly if there were no significant difference between the stresses (IV and I), the rectangles would overlap the X-axis. If the two tests were the same, the bivariate means would lie along one of the axis.

Again the stress response was only evident at the highest ambient temperature, greater than 1 standard deviation, but none of the baseline measures were significantly different from zero, although all the means were negative. There might have been a skew in the data if the sampling window were consistently lined up off the centre of the perineal area; however, this was not evident on review of the thermographs.

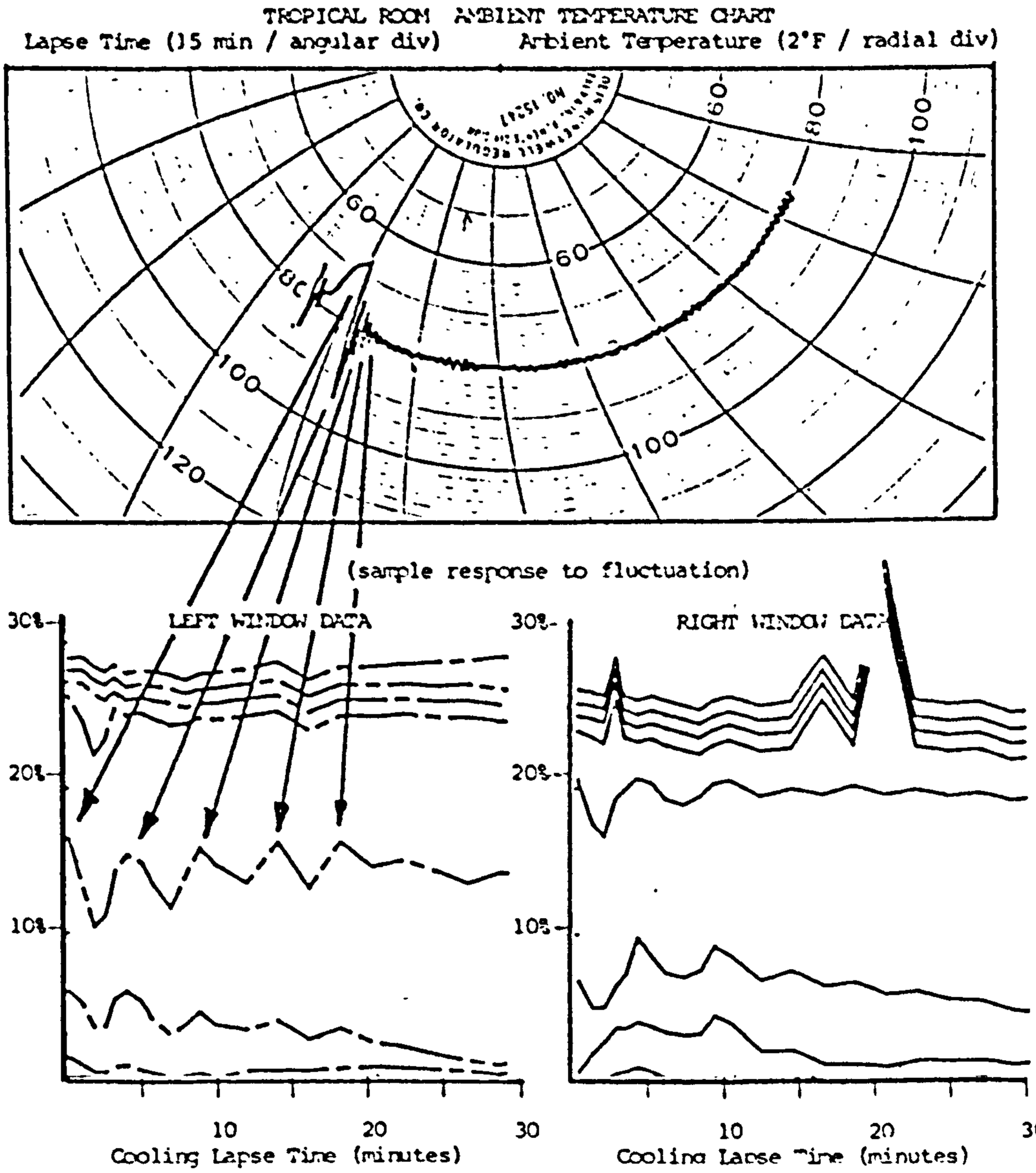
The impact of ambient temperature on seating thermography is such that hyperaemic reactions may be extended and more readily identified at higher ambient temperature. Lower ambient temperatures result in fast surface cooling visually demonstrating temperature gradients rapidly but they did not improve quantitative characterization of cooling responses. It appears that ambient temperatures in the low twenties (normal comfort ranges) is adequate for design of a clinical examination booth.

5.2.5 Fluctuations in Ambient Conditions

5.2.5.1 ambient temperature

Throughout the various phases of the experiment, it was found that differences in ambient temperatures of plus or minus 0.5°C, within any experimental period, did not result in overt distortion of the data. Variations out of this range, however, interfered with the cooling process as seen in Figure 5.18. Besides the noise spike problem mentioned earlier, a periodic variation can be seen, beginning at time zero and continuing noticeably to the thirty

FIGURE 5.18 EFFECT OF AMBIENT TEMPERATURE FLUCTUATION ON AREMETER DATA



minute mark. It is quite difficult to realize that a stress of level IV is being charted on the right side.

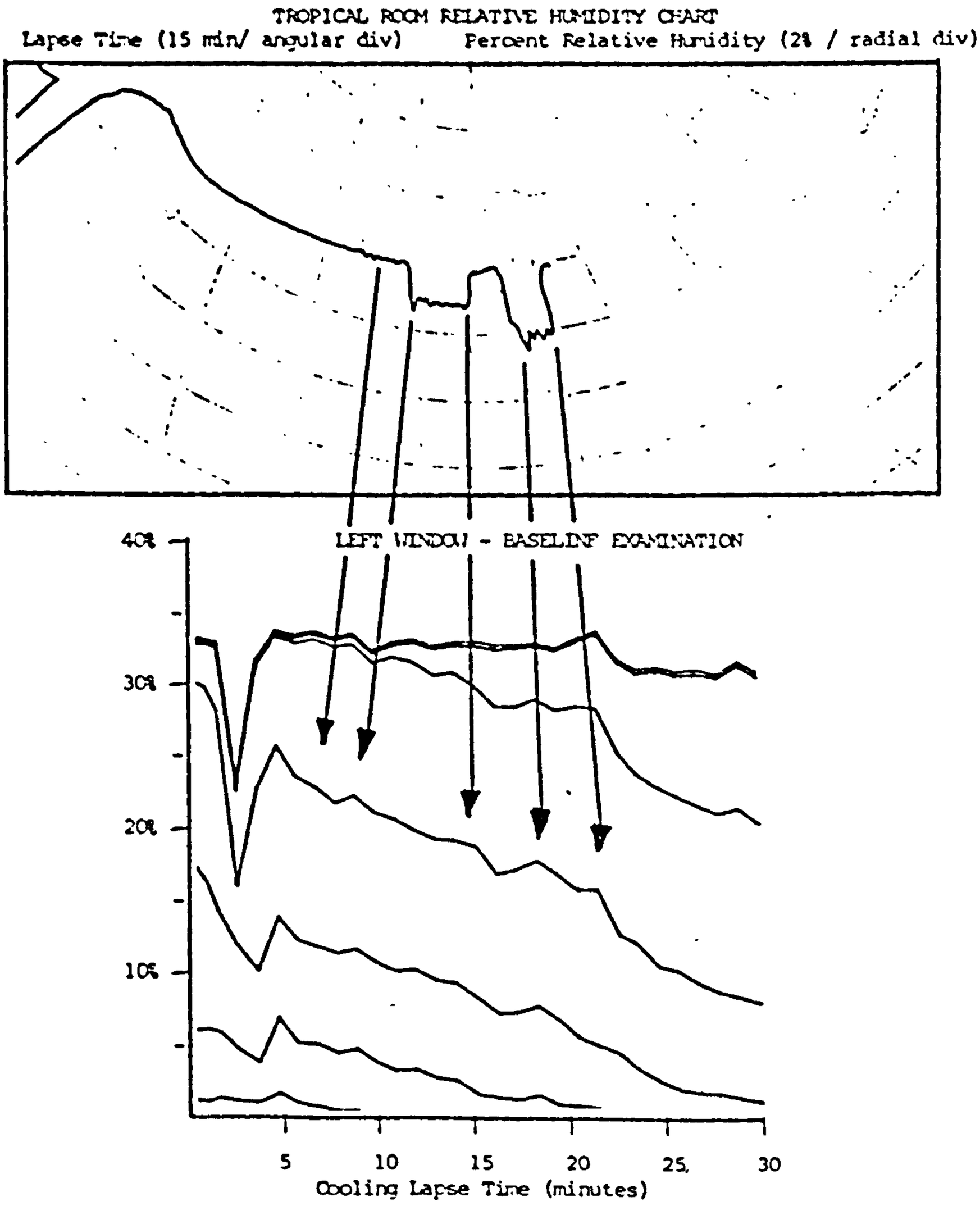
In examining the centrally displaced isotherm of the left graph of the accumulated percentage area curve, one can count at least nine maximum and minimum values. Referring to Figure 5.19, the monitored temperature of the environmental chamber, only an approximate comparison can be made considering the low resolution of the time scales.

5.2.5.2 relative humidity

The sensitivity of the quantitative data to changes in ambient temperature was most readily appreciated when a step change was introduced during the course of an examination. A similar step change was also conducted with the relative humidity (RH), by implementing the following changes: 40-45% at 5 min., 45-40% at 15 min., 40-50% at 20 min., and 50-40% at 25 min., see Figure 5.19. If the thermographic data were sensitive to these environmental changes, oscillations in the cooling curves would be observed. Baseline examinations were used for three subjects and environmental hygrometer charts used to record the induced atmospheric changes. In addition, a Wet Bulb Globe Thermometer (WBGT) was in operation, adjacent to the examination plinth, to confirm the changes set in the control room.

A steady cooling trend was perceived, indicating that sudden changes in relative humidity were not altering the results significantly. The influence of relative humidity changes is most acute when the subjects skin is just wetted so that the ambient temperature should not be so high as to induce profuse sweating. On the basis of these tests it is concluded that if changes in Relative

FIGURE 5.19 EFFECT OF AMBIENT RELATIVE HUMIDITY FLUCTUATION ON AREAMETER DATA



Humidity within the OCCC thermography examination room were kept within comparable limits to those used in these tests the results of the tests would not be compromised.

5.3 DISCUSSION

5.3.1 Data Quality

The three main categories of thermographic data examined are: visual, maximum and mean imaged temperatures. All are complementary in studying the thermal events taking place at the surface of the skin. The best visual record was obtained by the cine film which provided a continual record of the isotherm changes. An optical analyser projector permitted review of the film at any speed to highlight dynamic phenomena. Stress responses were characterized by local skin temperature increases of several degrees over a period of several minutes the subsequent cooling took place continuously for the observation period of 30 minutes.

By reviewing the first few minutes of film slowly, transient hyperthermic changes were readily identified, while a high speed review of the later cooling process was used to locate those specific sites which differed from the general rate of cooling. More detail was seen at a sensitivity of 0.5°C per isotherm, but generally, the magnitude of temperature change necessitated recalibration during the 30 minute period. It was, therefore, found to be more convenient to use a lower sensitivity, 1 C° per isotherm, and to observe this process without changes in the calibration of the temperature scale.

The maximum temperature plots were also sensitive measurements of hyperthermic responses, but were subject to observer error due to the manual measurement technique. This type of information might be

collected automatically with a surface contact thermistor or a narrow angle radiometer.

The graph of accumulated area versus time, with the highest temperature channel being closest to the time-axis, generated a display which accentuates localised increases in skin temperature. This measure is useful when such reactions last longer than the minimum patient preparation time.

Mean imaged temperature calculations permitted compression of the isotherm data to a single locus. Comparison of such mean temperature data may then be accomplished with comparison of characteristic points or by modeling the complete curve.

The initial analysis indicated that the influence of localized temperature changes could be swamped by other sites at elevated temperatures. The size and location of the data sampling window were considered crucial.

To apply thermography successfully in a clinical environment, it is necessary to maximize the relative size of the actual suspect area by using close-up views of the subject. A constant minimum distance should be used, with the camera's optical axis kept normal to the surface of that tissue. It was considered important in this quantitative application to examine the patients as quickly as possible after sitting; however, in the clinical setting, patient handling is a limiting factor. In addition, the critical comparison for a specific patient may not be between the left and right sides of the sitting area, but rather between differing tissue states of one particular area, at different points in time.

5.3.2 Minimum Environmental Control For Clinical Thermography

The experimental run, during which there was a variation in ambient temperature, demonstrated the need to maintain control of room temperature within an approximate range ± 0.5C° during the examination. Changes in ambient temperature affect general cooling rates, and interfere with quantitative interpretation of variations in these rates if not held constant.

In examining the response of tissue of normal subjects to stress, there appeared to be no advantage to using a cold room temperature. The higher ambient temperature of 26.6°C appeared to extend the duration of hyperthermic activity ; however, the differentiation of surface temperature patterns was slowed. Since a short examination is preferable in clinical situations an ambient temperature of 21°C was recommended for the thermography room at OCCC.

Draughts will influence cooling rates by convection and asymmetrical thermal patterns may be misinterpreted. For this reason, the examination table at OCCC was equipped with a screen to shield the subject from ambient air streams.

5.4 SUMMARY OF FINDINGS

1) Time-lapse photography provides a method of subjectively reviewing thermographic data and cognitively appreciating variations in topical cooling rates. Transient and persistent phenomena can be distinguished with highspeed reviews of the data. However, infrared emissions, associated with pressure induced ischaemia, frequently arise from a very localized superficial source. For this reason, the camera should be at a close range when used in conjunction with quantitative equipment.

2) Accumulated area displays provide a sensitive measure of hyperthermic changes during the first few minutes of hyperaemic skin reaction.

3) Skin temperature during the first thirty minutes after prior loading reaches a maximum within the first three minutes ranging from 1.5 to 3.0°C for control subjects.

4) The most sensitive measurements were obtained with the thermograph at minimum range, and the sensitivity set at 0.5C° per division. Over a thirty minute cooling period this required recalibration, but for fifteen minute cooling periods it does not.

5) The ambient temperature ranges tested, all permitted detection of hyperthermic responses, with greater cooling at the lower ambient temperatures, 18.6°C and 21.0 °C.

6) Ambient temperature fluctuations should not exceed ±0.5C° during the examination period.

7) Relative humidity fluctuations of up to twenty percent did not prevent detection of the expected cooling curve. It was impossible to introduce larger changes without accompanying ambient temperature fluctuations greater than the 0.5C° limit.

8) The general recommendation for the thermographic room at OCCC was to monitor both ambient temperature and relative humidity, and to install equipment which would maintain a humidity range of ± 10% during the examinations.

CHAPTER 6: AREAMETER ANALYSIS OF THERMOGRAPHIC DATA

6.0 INTRODUCTION

In this chapter the results of clinical research studies are reported, emphasizing automatic analytic techniques. The temperature data were normalised by calculation of mean image temperatures and tested for parameters which influenced skin temperature cooling. Comparisons were based on data obtained from baseline and post-sitting examinations, sampled at lapse times of 5 and 15 minutes. Additional characterization of skin cooling was explored by modeling the mean imaged temperature versus time curves with a second order power fit polynomial. Coefficients were calculated and plotted against each other on scatter graphs. Observation indicated the presence of a linear relationship between two coefficients.

6.1 METHOD

6.1.1 Study Population

The areameter analyses discussed in this chapter are based on OCCC patient and research studies, a subset of those patients presented in Chapter 4. In Appendix I, the patients examinations are listed by type in addition to a personal profile including age, sex, tissue site (localized by the areameter data window), tissue quality (classified in chapter 4), seating system and duration of sitting time. This information is summarized in Table 6.1, by an age distribution histogram and a bivariate frequency distribution of seating systems and sitting times.

TABLE 6.1 SAMPLE POPULATION

Seat Types — Bivariate Distribution of Data Samples

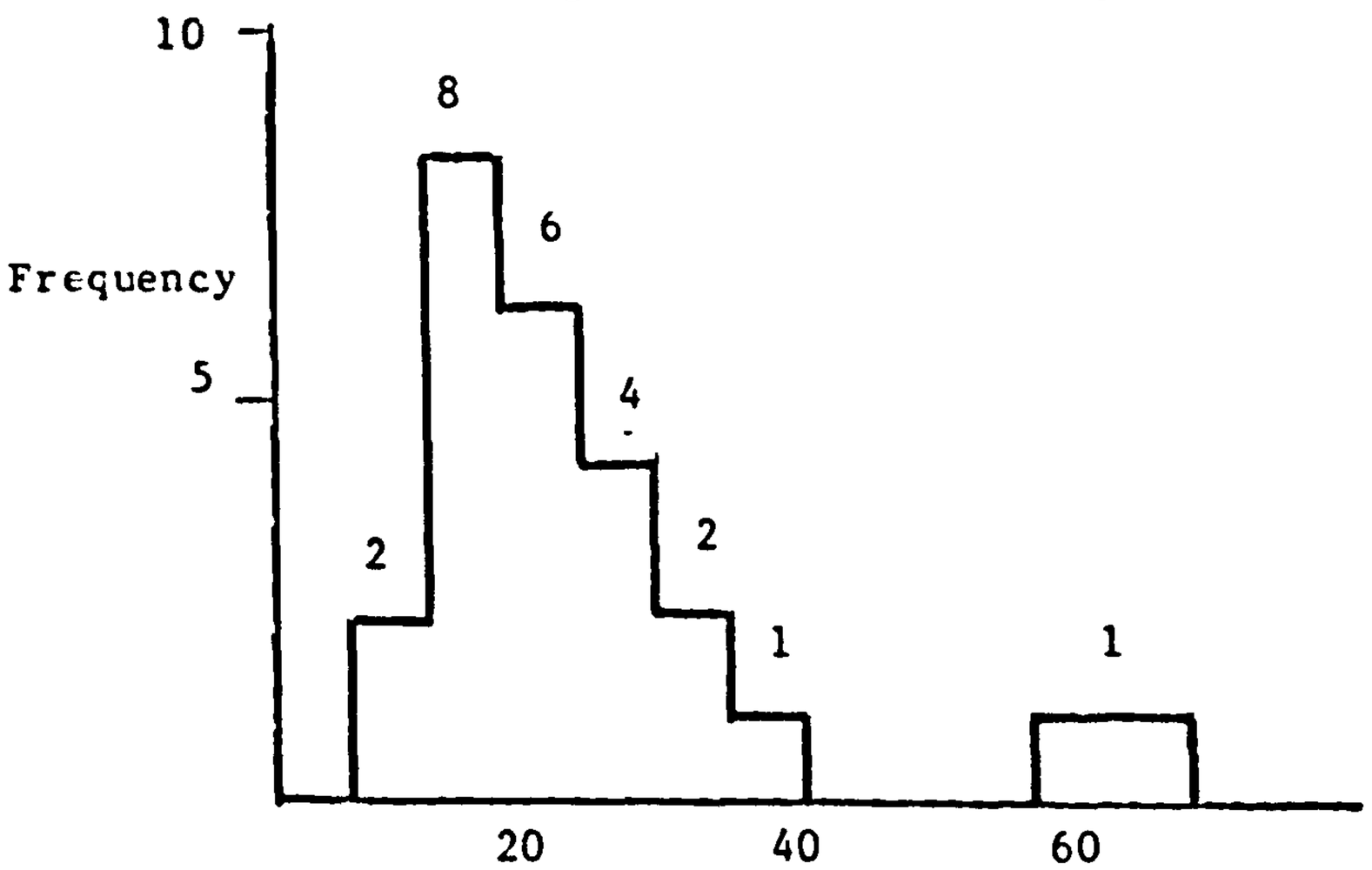
	0	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	6.0
Contoured	3	1								
Foam	2		2		1	1		2		
Standard Care	2			2						1
Roho	17	7	3	4		3		2	2	5
Gel		1						1		1

Sitting Times (HR)

Subject Types
N = 24 subjects
Male 8
Female 16

Examination Types
n = 70 examinations
Screening (8), Sitting Tolerance (22)
Research (24), Status Check (12)
Review (4)

Age Distribution Histogram



One subject was available for intensive research trials and the rest participated in these studies, as part of their overall seating management programme.

6.1.2 Environmental Condition

Because fluctuations in ambient temperature and relative humidity were undesirable, the following modifications were made to the thermography room at OCCC:

a) addition of an airconditioning unit;

b) modification of the entrance door to seal against rapid air exchange;

c) installation of both a humidifier and dehumidifier; and

d) provision of a draught screen for the examination plinth.

The ambient conditions were continuously monitored by an electrical dry and wet bulb hygrometer integrated into the areameter data through a multiplexer, see Appendix IV for details. The display of areameter data included a separate display of these environmental measures, so that changes occurring during the examination, such as an influx of warmer hallway air when the exit door was opened, were recorded and displayed with the data.

Tests were conducted to ascertain the environmental stability of the examination room. A floor to ceiling moveable pole was prepared with thermistors, attached at one foot intervals. Dry bulb temperatures were sampled for 15 minute periods throughout the room, at 3 foot intervals referenced from a grid taped to the floor. Within the test zone, immediately around the plinth, the detected

temperature variations were less than 1°C. These results indicated that the minimum conditions recommended in Chapter 5 were met.

Relative humidity changes over the year were determined, by a review of previous patient examination records. Without an airconditioner and humidifier the relative humidity ranged from (25% to 85%) from winter to summer. This range was reduced, (35% to 70%), after the modifications and based on the variation of relative humidity which rarely exceeded ±10% during examinations.

An anemometer was used to measure draughts within the thermography chamber, thus detecting the presence of currents from the air conditioning system which might affect the thermographic data. No measurable air velocities were detected in the vicinity of the examination plinth (less than 1.0 foot per minute) or within the draft hood. These tests demonstrated that the area used for the seating tests was free from air currents which would cause asymmetrical cooling of the subject.

6.1.3 Instrumentation

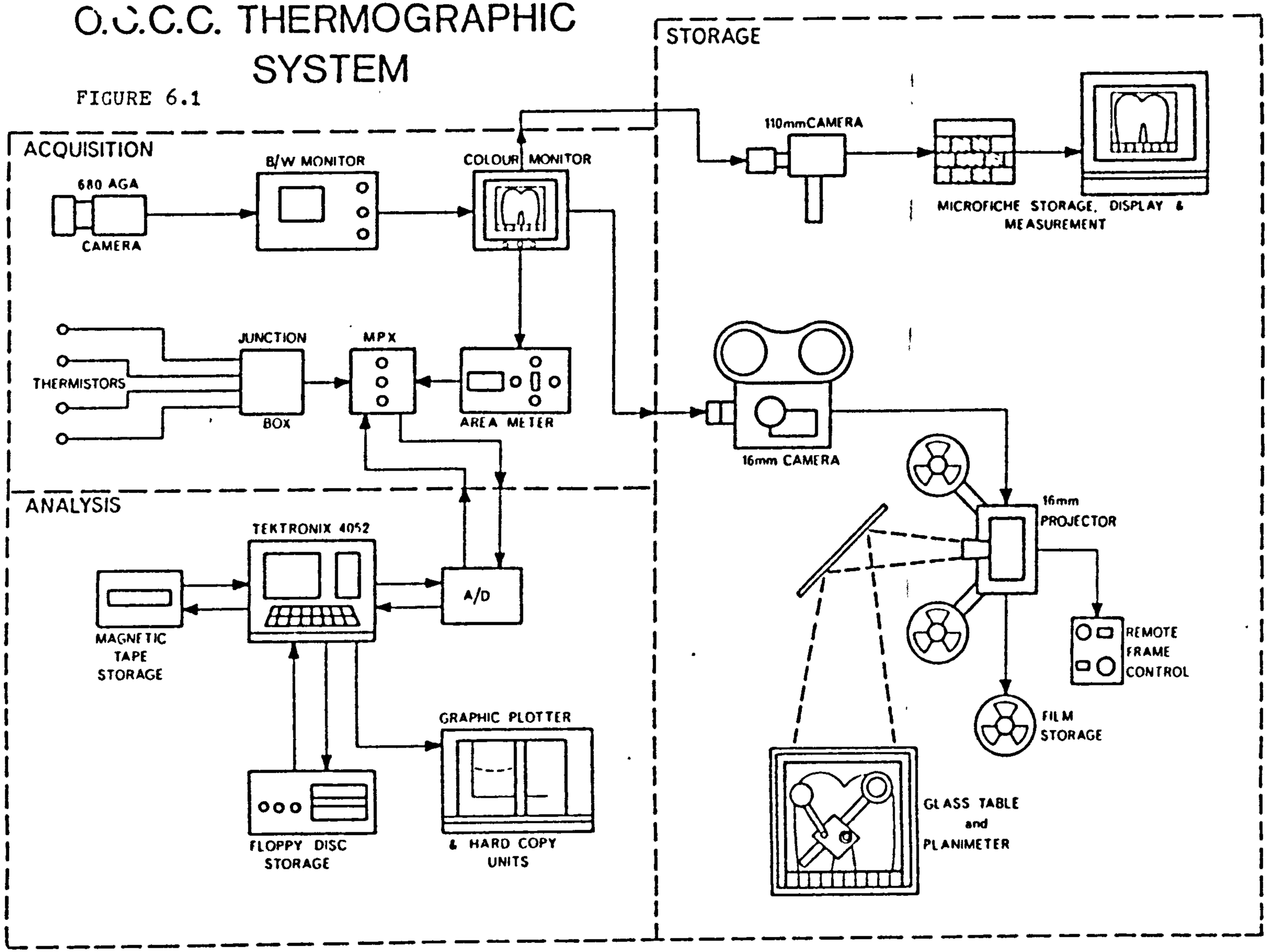
The thermographic system developed at OCCC had three sections; data acquisition, data storage and data analysis, see Figure 6.1 . The following instrumentation changes were introduced to the thermographic system, subsequent to the experience of the DCIEM experiments.

6.1.3.1 data acquisition

Thermistor sensors were included in the thermographic system to monitor the environmental changes occuring during an examination. They were operated through a multiplexer (MPX), controlled by the

O.C.C.C. THERMOGRAPHIC SYSTEM

FIGURE 6.1



Tektronix 4052 graphics microcomputer. This equipment permitted the simultaneous operation and sampling of the areameter.

6.1.3.2 data storage

Photographic records of thermographs are a compact and versatile storage medium. A 110 Minolta Camera provided a microfiche records of the subject's posture, type and condition of seating system, wheelchair fit, and skin colour immediately following pressure relief, see Figure 4.1. Colour photographs were taken of the subject's skin at the beginning and end of each fifteen minute examination to record any visual changes associated with tissue quality. Time-lapse cine films of the thermographs were reviewed on a variable speed projector to provide a subjective impression of differential cooling rates, and to record any movements of the subject within the field of view.

6.1.3.3 data analysis

The computer control and data analysis software was written for both the Tektronix 4051 and 4052 Tektronix microcomputers. The data were stored immediately after completion of an examination, on either magnetic tape or floppy disc. The accumulated percent area graphs, described in Chapter 5, were displayed in real time, so that the investigator could observe the development of cooling trends as they occurred. This was very useful when the data demonstrated a prolonged hyperthermic reaction a warning of tissue risk could be communicated immediately to both patient and physician to facilitate any rapid decision making about the patient's management. Mean imaged temperature versus time loci were generated off line for comparison of intra- and intersubject trends.

6.1.4 Protocol

6.1.4.1 patient examinations

The patients particpating in the thermographic trials followed the examinaton protocol outlined in Table 6.2 with the following modifications:

TABLE 6.2 Protocol For Automated Data Collection

(addition to Table 4.1)

9	b) View - close up of bony prominence - 1/4 field target size Sensitivity - 1 and 0.5 C°/div. Thermographs - recorded at: microfiche (2,5,10, and 15 min.); polaroid (15 min.); and cine (continuous). Photographs - recorded at: microfiche (2 and 16 min.) Foil markers applied at within the first 5 minutes Core temperature was measured at (5 and 10 min.)

In addition, the following steps were developed to streamline the collection of quantitative data. It was apparent in the DCIEM trials, that foci of increased infrared emissions may arise from very localised sources. The thermographic camera had to be used at its minimum focal length to increase the relative size of these sources in the field of view. It was, therefore, most convenient to leave the data window at a constant size in the centre of the display screen. Alignment and focus could then be achieved by positioning the camera, while watching the video image for targetting.

The lapse-time counter was started immediately prior to the subject's transfer to the plinth. It took from one to three minutes to prepare the patient and position the thermograph camera, depending upon the size and frailty of the patient. The examination plinth had a horizontal, elevating anterior section, which brought the subject into the flexed hip and knee position. Lateral hip pads were found to be necessary to prevent any small movements which might introduce artifacts into the data.

Small self-adhesive foil markers were used to locate the borders of the computer window on the subject's skin, and the position of the markers was drawn directly on the video screen. These anatomical reference points facilitated the visualization of relative movements during the recording of both thermographic and photographic data.

6.1.4.2 research examinations

On the first day of participation the following examinations were con ducted to develop a risk profile and to ensure that the subject's skin was healthy and intact, prior to seating trials.

i) Risk Assessment: A thermograph was taken, prior to the subject's sitting, providing a preliminary map of his thermal anatomy. A local inflammation was found over the coccyx of subject (RR) , and his seating was modified to provide complete pressure relief over this site. As a precaution the test seats were provided with lumbar support to counteract his kyphotic posture. Marked healing was noted within the first week of trials.

ii) Baseline Examination: The subject arrived, having not sat during the previous twelve hours. He was thermographed to record the stable skin temperature pattern, which provided a basis of comparison for subsequent baseline examinations and post-sitting tissue responses.

iii) Sitting Trials: Following the baseline examination, the subject began a period of test sitting. On completion the subject was transferred to the examination plinth, and the thermographic recording initiated as quickly as possible. The baseline examination and skin history identified the target zone of highest risk.

6.2 ANALYSIS

6.2.1 Visual Data

Qualitative thermographic records included both microfiche serial still thermographs and time-lapse cine films. In addition, photographs were taken of the patient's skin, wheelchair posture and seating system. The latter data was nominally coded (i.e., type of seating system) and the former reviewed on a patient by patient basis both for clinical decision making and as source data for the study described in chapter 4.

6.2.2 Analysis of Areameter Data

The immediate display of areameter data was in the accumulated area versus time format to enhance any hyperthermic response. This response occurred during the first few minutes after pressure relief in able-bodied subjects; however, patient data frequently did not

include valid samples within this time frame, owing to the required preparation time. The later cooling response was more accessible and the analyses were used which detect significant characteristics in this later phase of skin cooling.

The first step in simplifying the data, was the calculation of mean image temperatures. Again average mean image temperatures were calculated at selected lapse times for specific groupings of the data to detect which parameters influenced the skin cooling rates.

In the second analyses various curve fitting expressions were tested to match and characterize the mean imaged temperature following release of loading. Coefficients were calculated for a second order power fit in an attempt to characterize the cooling process. The mean imaged temperature plots were initially normalized, using a cubic spline fit programme, with both a second and third order polynomials for observation without calculating coefficients:

1) linear ($\bar{T}$ vs t)

2) quadratic (parabolic curve) ($\bar{T}$ vs t)

3) linear fit to a semi-log plot (ln $\bar{T}$ vs t)

4) quadratic fit to a semi-log plot (ln $\bar{T}$ vs t)

Further analysis was conducted using curve fitting programmes which provided estimations of the polynomial coefficients. The first order equations were thought to be inappropriate due to the exponential nature of Newtonian cooling and the third order fits were too unstable, varying dramatically for small changes in a single sample point.

The basis for comparison was then simplified to studies of coefficient changes in the second order polynomial expression. The quadratic fit of the semi-log mean imaged temperature plots was selected for this preliminary analysis, as it seemed to combine the favourable characteristics of providing shape information and ease of analysis (three unknowns).

The parabolic curve was defined by the following expression:

$$\ln \bar{T} = a + bt + ct^2$$

where t time
and a,b,c coefficients of the polynomial

The coefficients were determined by solving a least squares fit of the average temperature data. The equation was rewritten as:

$$\bar{T} = k_0 e^{k_1 t + k_2 t^2}$$

where: k_0 e ^{a}
k_1 b
k_2 c

These k values were calculated and stored in independent matrices. They were then plotted as coordinates on three axes (k_0, k_1 and k_2), against each other as scatter graphs. Samples were studied to identify possible groupings, which might appear related to external loading conditions or to tissue quality. Means and standard deviations were tabulated for comparative groups of data, to detect specific sensitivities of these coefficients to test conditions.

6.3 RESULTS

6.3.1 Sample Case Study

The early development of the areameter routines in the OCCC studies identified a number of technical problems, illustrated by the following case study.

Subject #A: (FM)

This patient was seen as an in-patient, while recovering from a pressure sore. He particpated in a number of studies to determine the seating arrangement best suited to his complex lifestyle. Because he spent a large proportion of his time walking with the aid of crutches, he was regarded as an irregular sitter. The tissue site at highest risk was his left ischial tuberosity, Figure 6.2, where the quality of the underlying tissues was considered poor.

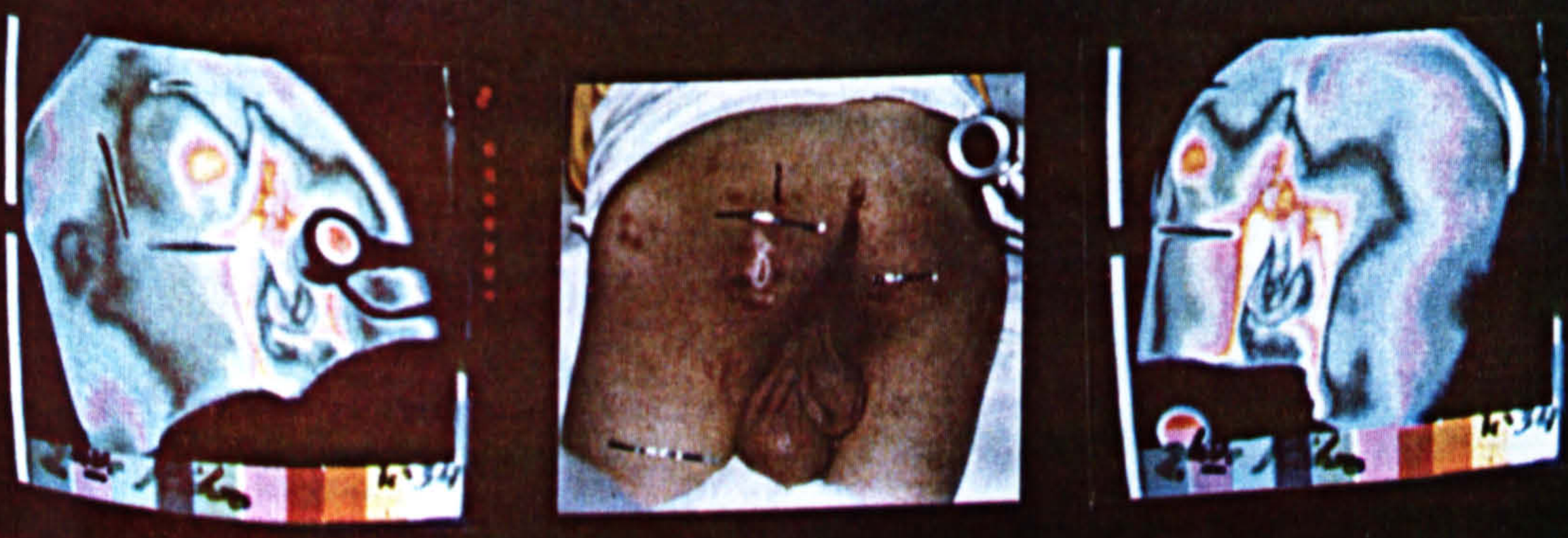
The emphasis of the areameter study was to determine the response of the freshly healed tissues to the stress of sitting. Foil markers indicated the location of the outer boundary of the data window. Initially, a large data window was used, see Figure 6.2a, resulting in a high ratio of perineal to ischial high temperature sources. In Figure 6.3 the corresponding areameter data can be seen for which the cooling curves decay smoothly.

A second examination, taken several weeks later when the subject resumed sitting, employed a smaller data window, (Figures 6.2b and 6.4) to examine the specific changes occuring over the left ischial tuberosity after a sitting stress. The initial sharp increase in area during the first minutes was the result of artifacts caused by the delay from time zero in preparation of the patient. The subsequent cooling curves demonstrated that all the temperature channels decreased within the first twelve minutes, although a substantial "jog" is seen. This was found, after review

FIGURE 6.2 CASE STUDY: SUBJECT A

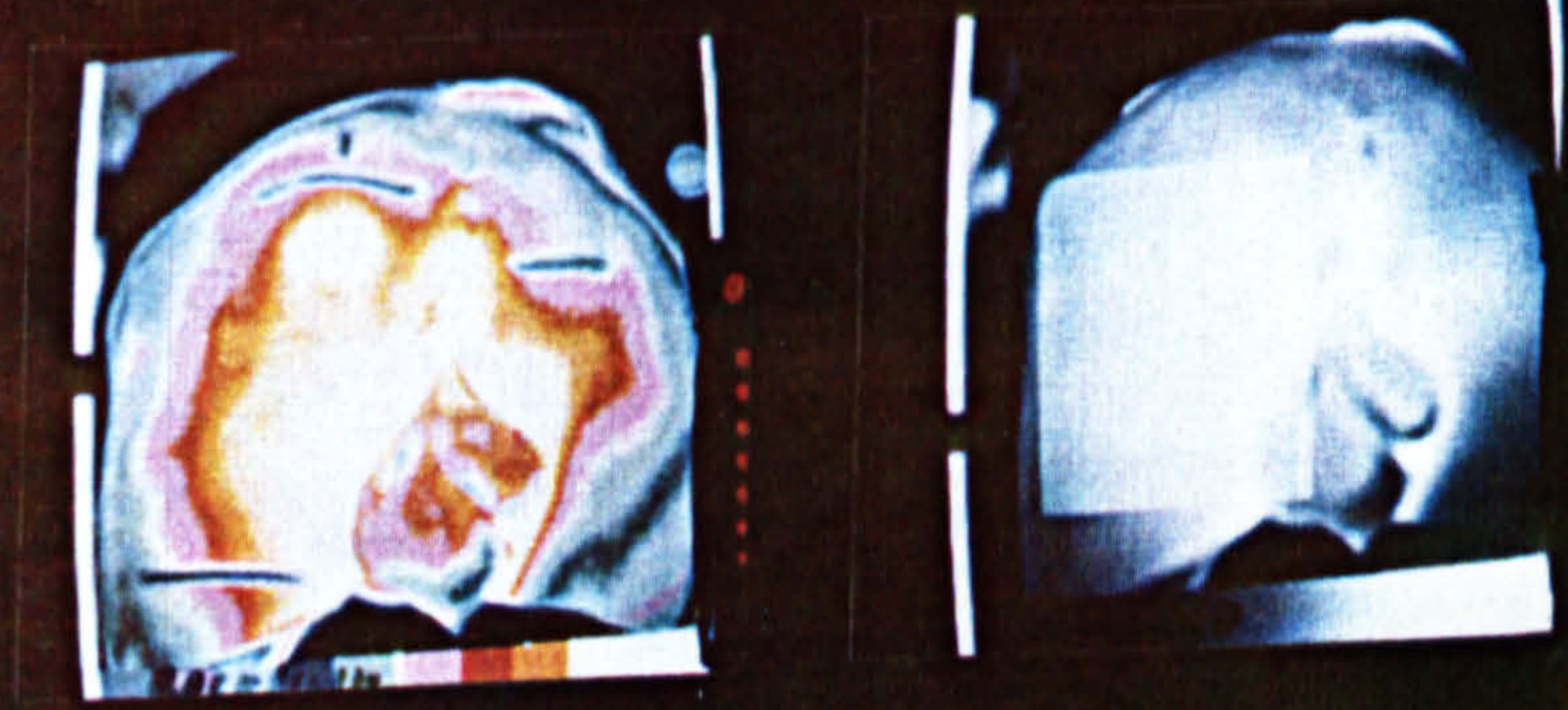
SUBJECT A

Problem Identified

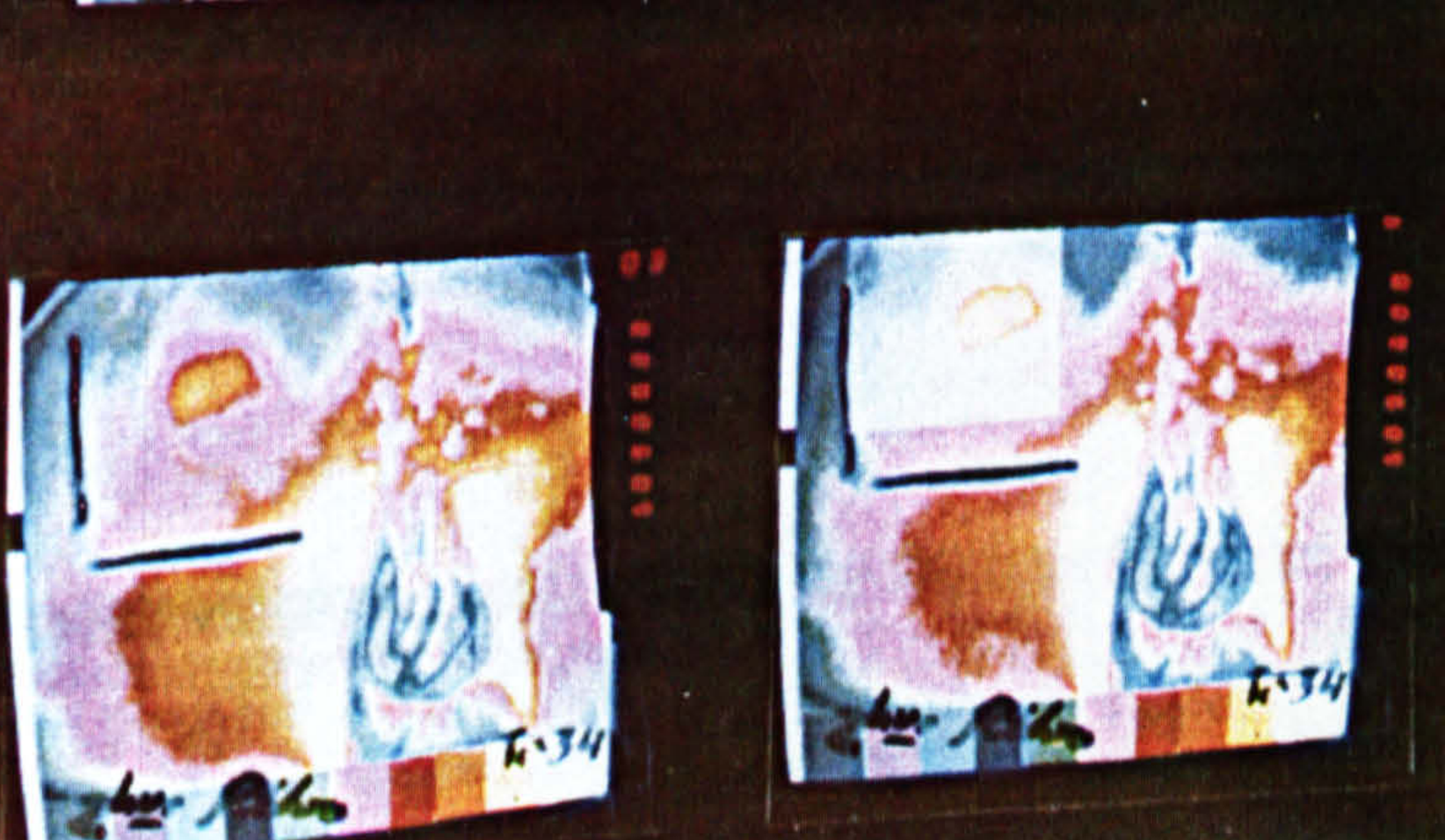


Window Selection

Noise



Movement



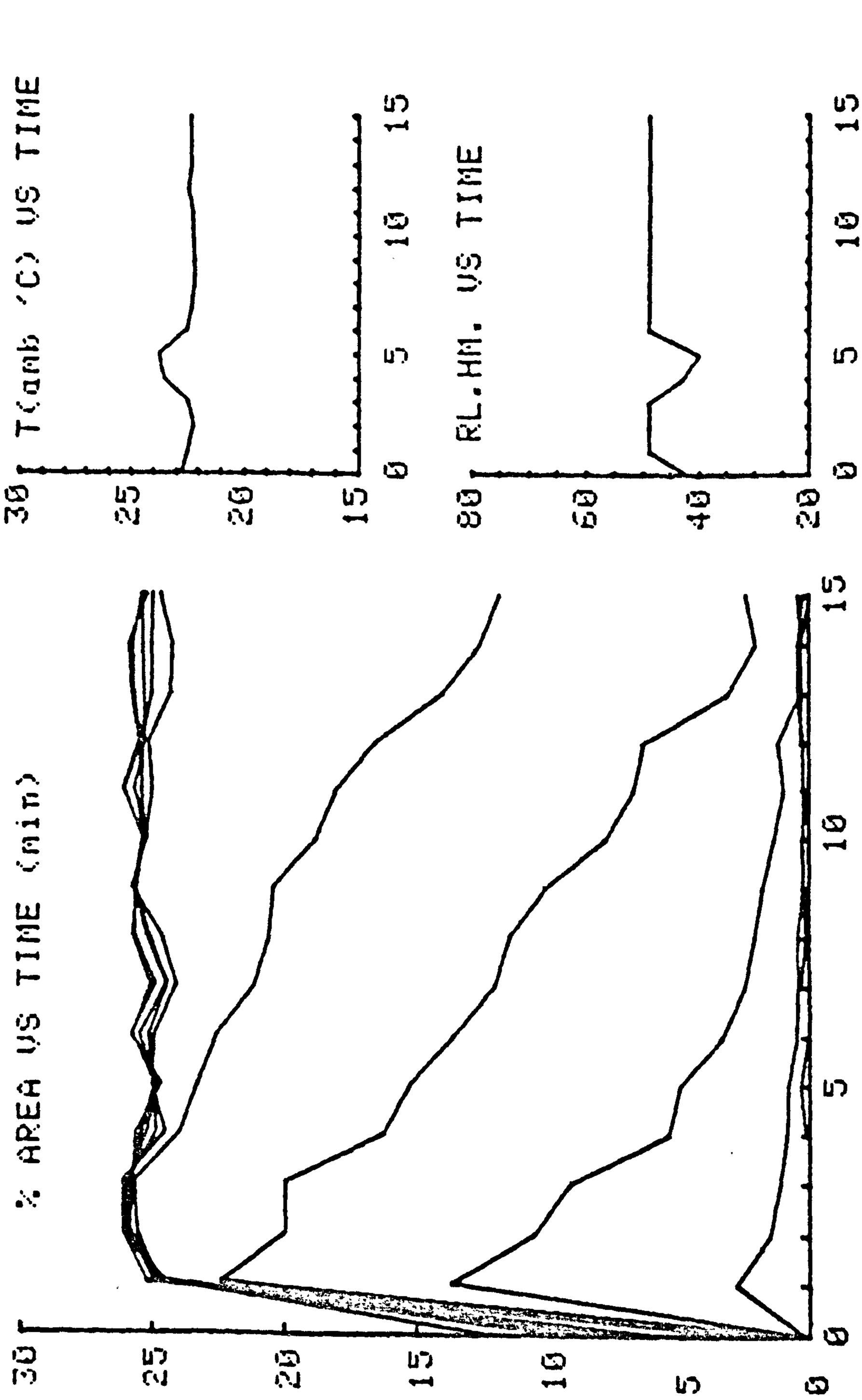


FIGURE 6.3 LARGE DATA WINDOW

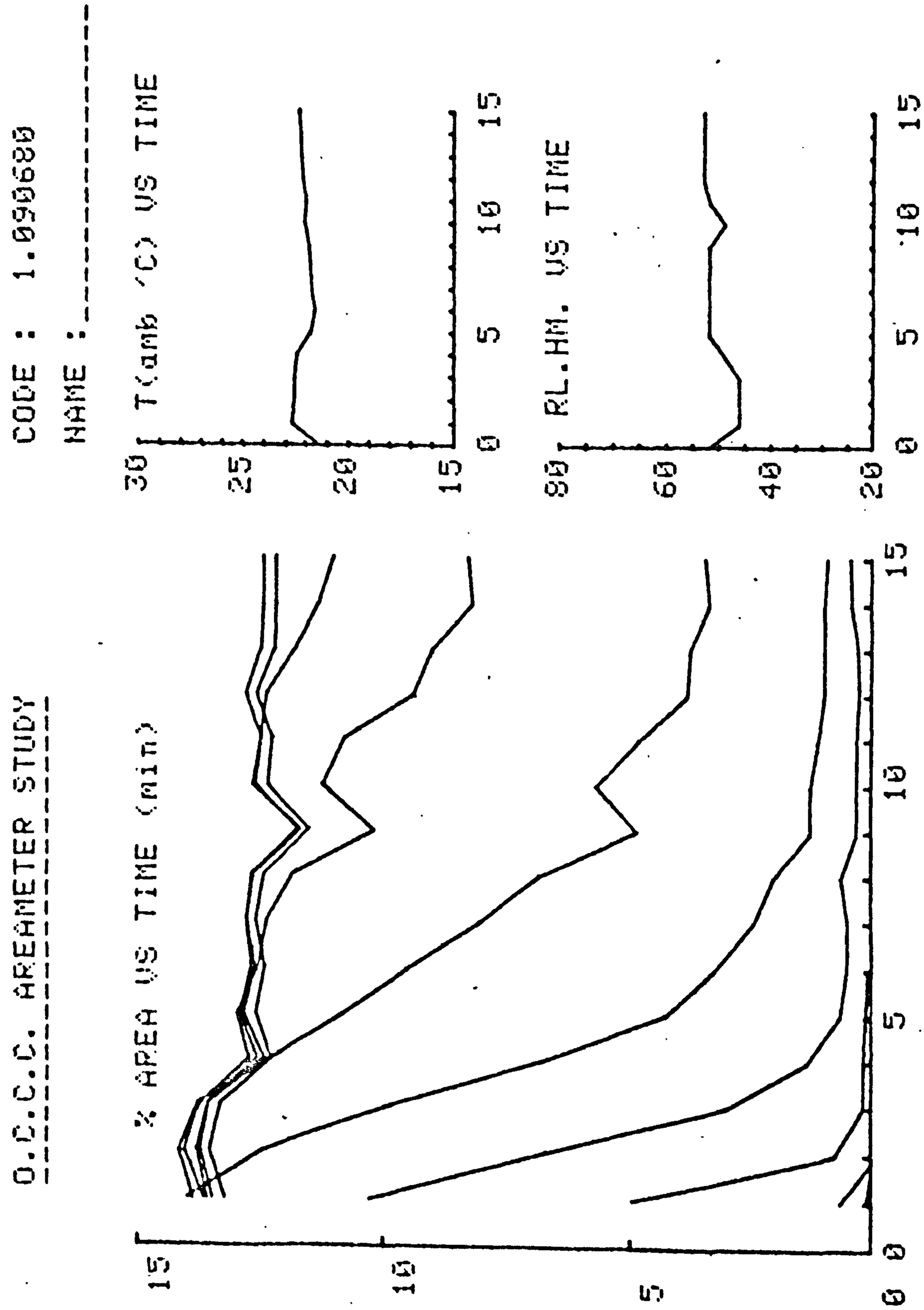


FIGURE 6.4 SMALL DATA WINDOW

of the cine film, to be the result of a small shift in position by the subject. This close-up format provided the most sensitive data for following a small localized problem area, and also demonstrated the need for hip blocks, to eliminate any movement by the subject during data acquisition.

6.3.2 Mean Imaged Temperature Comparisons

6.3.2.1 baseline comparison with sitting stresses

The first set of tests compare baseline and sitting stresses to determine the sensitivity of mean imaged temperature measurements to stress response of tissue. Examples were chosen to provide a maximum contrast as follows:

i) baseline vs sitting stress for the experimental subject on a Roho cushion, see Figure 6.5 ;

ii) baseline vs sitting stress for the experimental subject on a foam cushion, see Figure 6.6 ; and

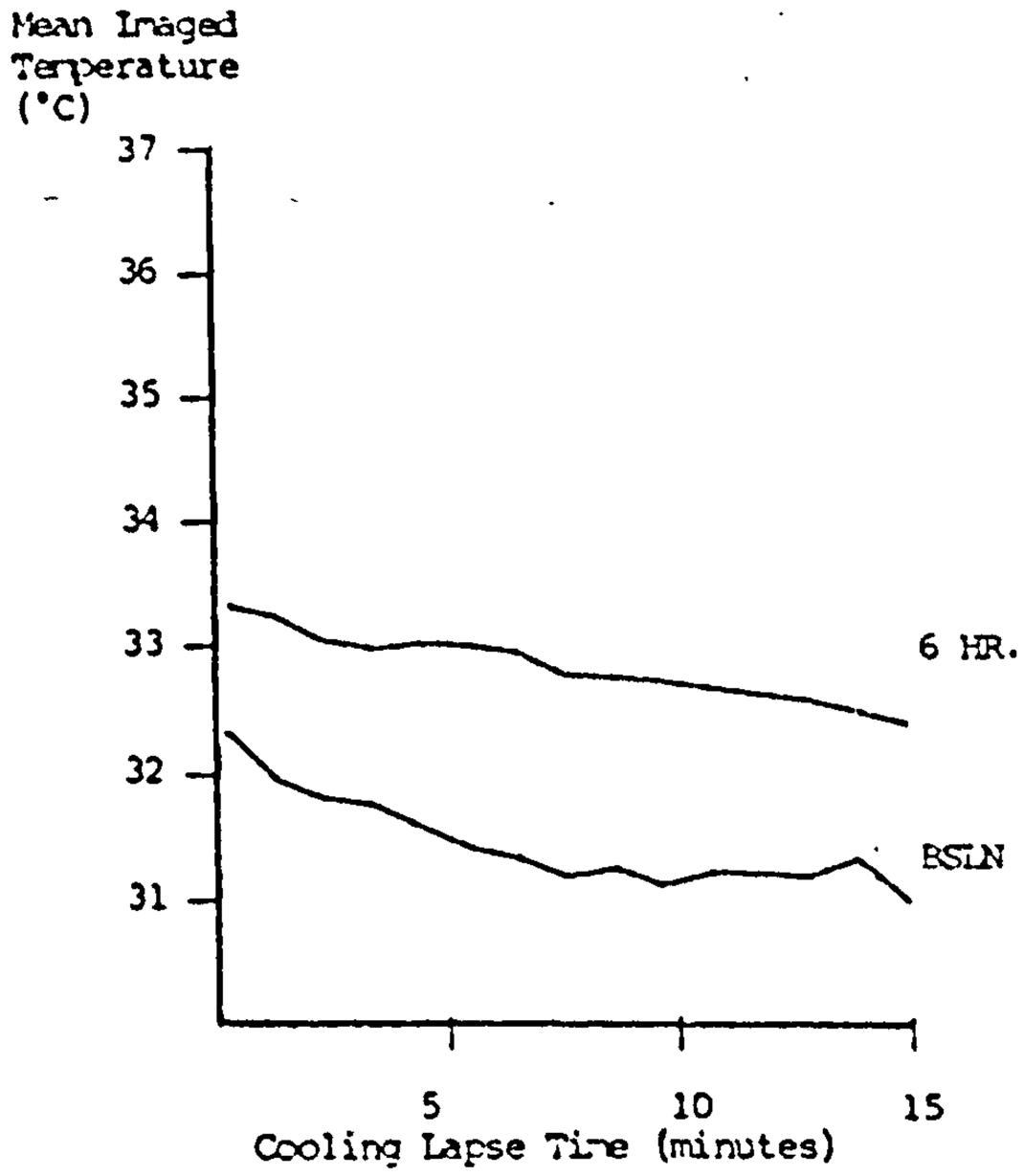
iii) baseline intrasubject variability, Figure 6.7

Average mean imaged temperatures were calculated for each of these graphs at at five minutes ($\bar{T}_5$), fifteen minutes ($\bar{T}_{15}$) and for the ten minute interval change ($\Delta\bar{T} = \bar{T}_5 - \bar{T}_{15}$).

The variability of the mean imaged temperature was such that the magnitude of 1 standard deviation was greater than the change of average mean imaged temperature over the ten minute cooling period from 5 to 15 minutes, see Table 6.3. This test was true for both multiple subject and single subject groupings of baseline tests.

FIGURE 6.5 COMPARISON OF BASELINE AND SITTING STRESS

(Subject RR - Roho Cushion)



AMBIENT CONDITIONS

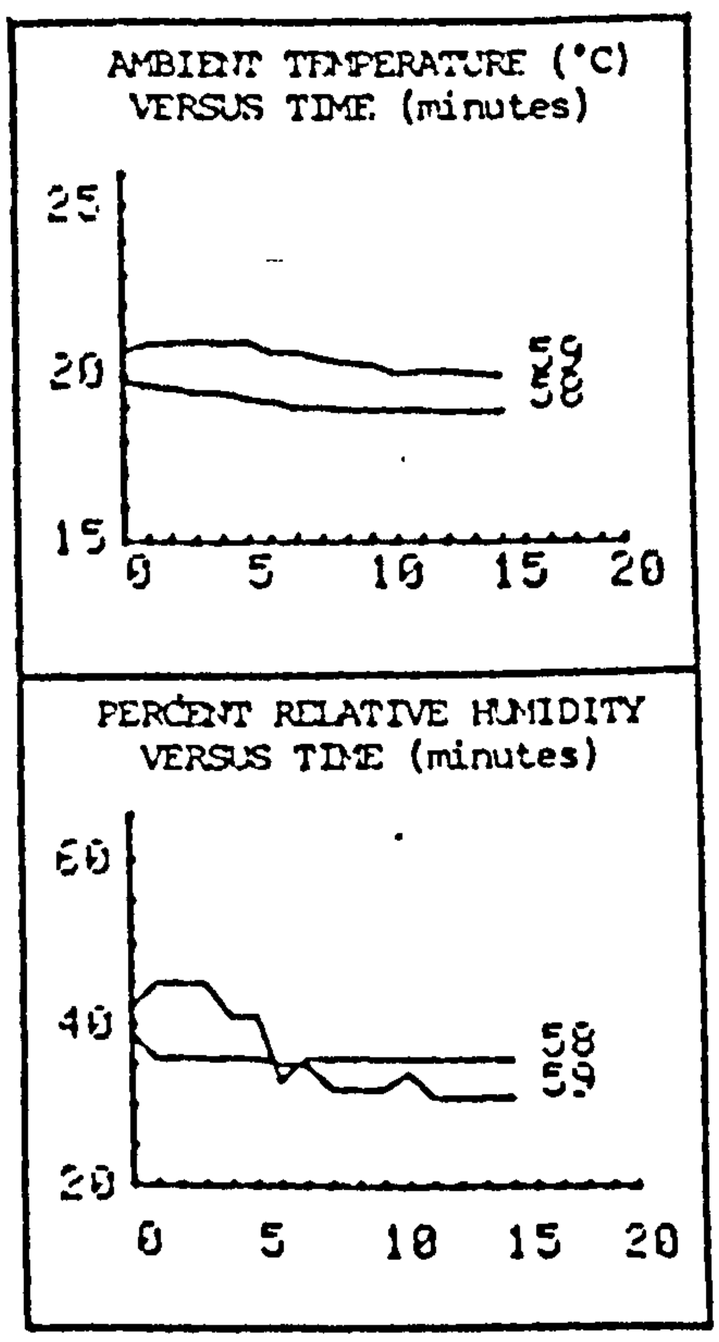


FIGURE 6.6 COMPARISON OF BASELINE AND SITTING STRESS

(Subject RR - Foam Cushion)

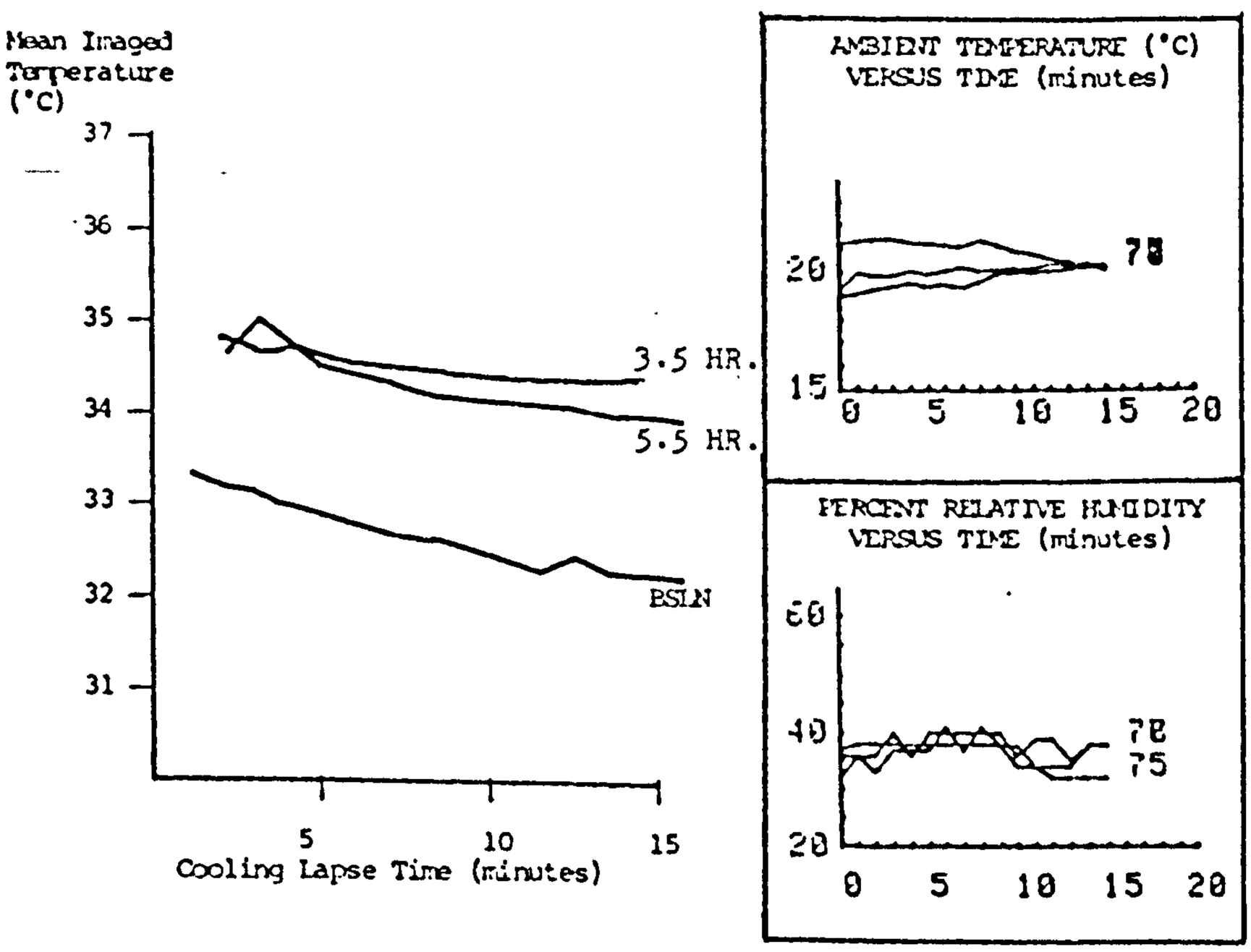


FIGURE 6.7 INTRASUBJECT VARIABILITY - BASELINES

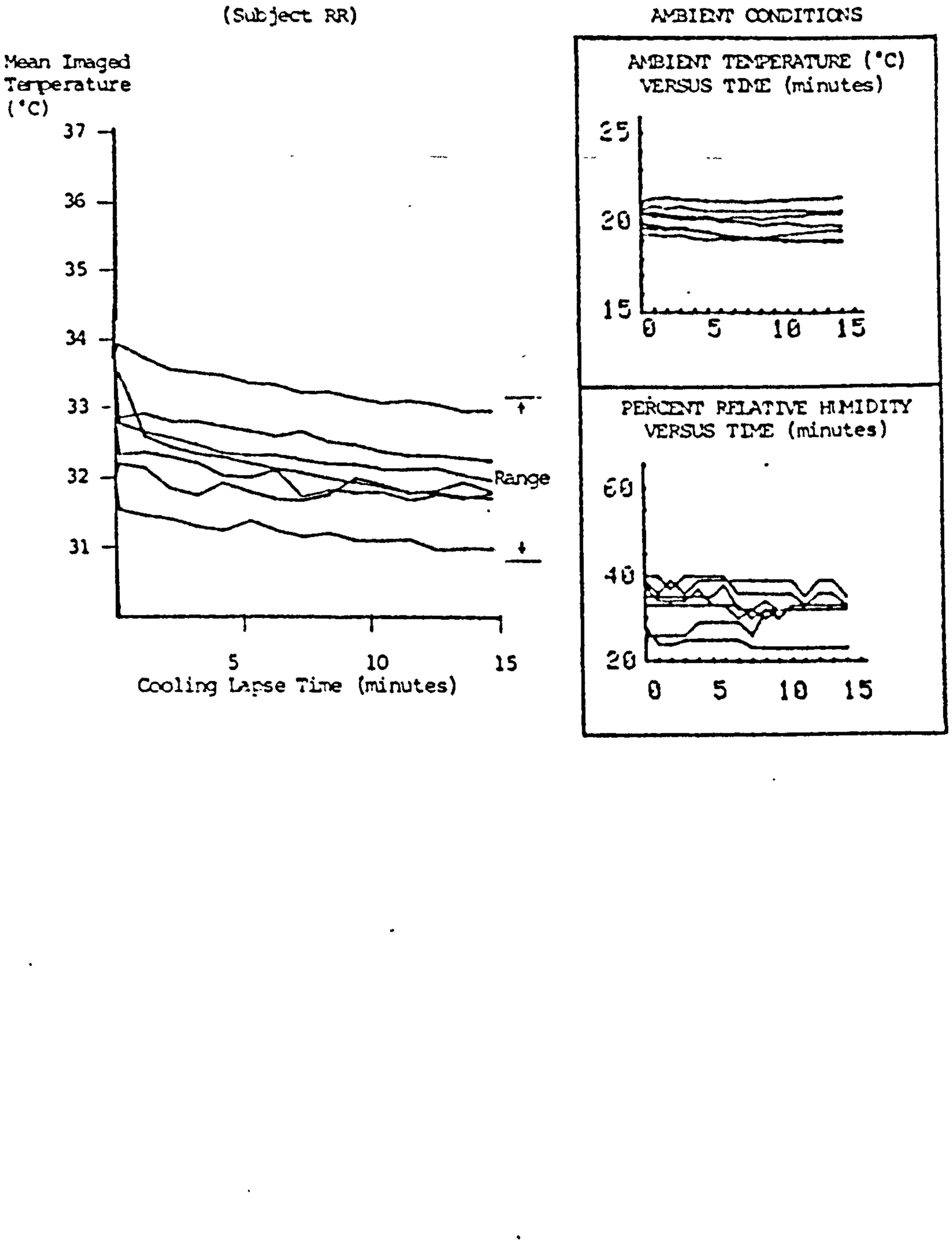


TABLE 6.3 Averaged Mean Imaged Temperature (Baseline Cooling)

Conditions	n	$\bar{T}_{5min} \pm 1\sigma$ (°C)	$\bar{T}_{15min} \pm 1\sigma$ (°C)	$\Delta\bar{T} \pm 1\sigma$ (C°)
All Subj. Baselines	13	32.8 $\pm$0.4	32.3 $\pm$0.8	-0.5 $\pm$0.2
Subj. RR Baselines	7	32.5 $\pm$0.7	32.2 $\pm$0.7	-0.4 $\pm$0.2

Although the ten minute temperature change ($\Delta\bar{T}$) represented a linear approximation of the cooling response, (-0.05 C°/min.); the magnitude of standard deviations for ($\bar{T}_5$ and $\bar{T}_{15}$) was greater than $\Delta\bar{T}$. Therefore no such approximation could be significantly different from zero with the available data.

For baseline examinations, the mean imaged temperature range for a 95% or ($\pm$ 2 σ) confidence limit, sampled at a lapse time of 15 minutes was 30.7°C to 33.9°C. In comparison, the maximum baseline skin temperatures for skin graded as healthy was 32.2°C $\pm$ 1.2C°, see Figure 4.9. Since the change in mean imaged temperature during the 5 to 15 minute interval of baseline cooling was ($\Delta\bar{T}$ = -0.5 $\pm$ 0.2), the range was (0.1 -0.9C°), defining a 95% confidence envelope. None of the ten minute interval $\Delta\bar{T}$'s for the sitting tests fell outside of this limit, indicating that the magnitude of

cooling was not sufficient to distinguish between stressed and nonstressed cooling responses. Damaged, or severely stressed tissue might remain at a high temperature, with little cooling during the examination, ($\Delta\bar{T}=0$). This infers that any predictor of tissue trauma by skin temperature should include at least two parameters to describe both the absolute temperature range and the amount of change.

6.3.2.2 influence of sitting stress on mean imaged temperature

Relative mean imaged temperature differences ($\Delta\bar{T}_R$) were obtained by subtracting the corresponding baseline from the post-sitting values. The significance of these relative temperatures was determined by comparing individual $\Delta\bar{T}_R$'s with the standard deviation for baseline examinations, (i.e., was the post-sitting temperature significantly greater than the baseline).

Mean imaged temperature for subject (RR) exceeded baseline temperatures by more than 2 σ, when the sitting time was greater than 3.5 hours, using either the Roho or Foam cushion, see Table 6.4

TABLE 6.4 Differential Mean Imaged Temperatures

(sitting stress minus baseline)

(Subject) Seat Type	Lapse Times 5min $\Delta\bar{T}_R$(C°)	15min $\Delta\bar{T}_R$(C°)	Sitting Time (HR)
(DF) Roho	-0.3	-0.6	0.5
(FM) Roho	-0.3	-0.7	2.5
(FM) Contour	+0.1	+0.4	2.0
(RR) Roho	+1.6*	+1.6*	6.0
(RR) Foam	+2.0*	+2.4*	3.5
(RR) Foam	+1.8*	+2.0*	5.5
(RR) Gel	+0.3	+0.9	5.0

* 2 σ for baseline mean imaged temperature (± 1.4 C°)

The Roho showed a significant increase in skin temperature response after loading for 6 hours; whereas, greater increases were observed for the foam cushions at almost half the sitting time. The gel cushion was considered a high pressure device but cooler than foam. This contrast in response raises the problem of understanding differences in short term skin reaction between cold and warm pressure . The gel and water cushions act as heat sinks until some equilibrium is reached.

6.3.3 Variability of Mean Imaged Temperature

6.3.3.1 parameters

Mean imaged temperature versus time graphs were plotted to review the data. The parameters used in these comparisons consisted of the nominal measures, subject and seat type; and the ratio measures, sitting time, mean imaged skin temperature and ambient temperature. The first test determined whether the reproducability of the results was dominantly influenced by factors associated with sitting conditions. Three parameters were used to group the data for comparative plots subject, seat type and sitting time, as indicated in the chart below, Table 6.5:

TABLE 6.5 Average Mean Imaged Temperature Comparisons

No. Test	Samples	Seat Subject	Sitting Type	Time	$\Delta\bar{T}max$ (C°)	$\Delta Tamb$ (C°)
#1	4	C	C	C	0.8	+1.1
#2	6	C	C	V	0.8	+0.5
#3	3	C	V	C	1.3	+0.8
#4	10	V	C	C	1.8	+2.0

Coding:

"C" denotes a constant (i.e., for subject - one subject)

"V" denotes a variable (i.e., for seat type - all seating systems included)

The sign of ΔT ambient was defined as +ve, if the highest ambient temperature and highest mean imaged skin temperature were both obtained from the same examination, as measured at a lapse time of 15 minutes.

The following measurements were made to determine which parameters introduced the greatest differences in mean imaged temperatures:

n the number of samples

$\Delta\bar{T}_{max}$ the largest range of mean imaged temperatures

ΔT_{amb} the largest range of ambient temperatures

6.3.3.2 influence of ambient temperature

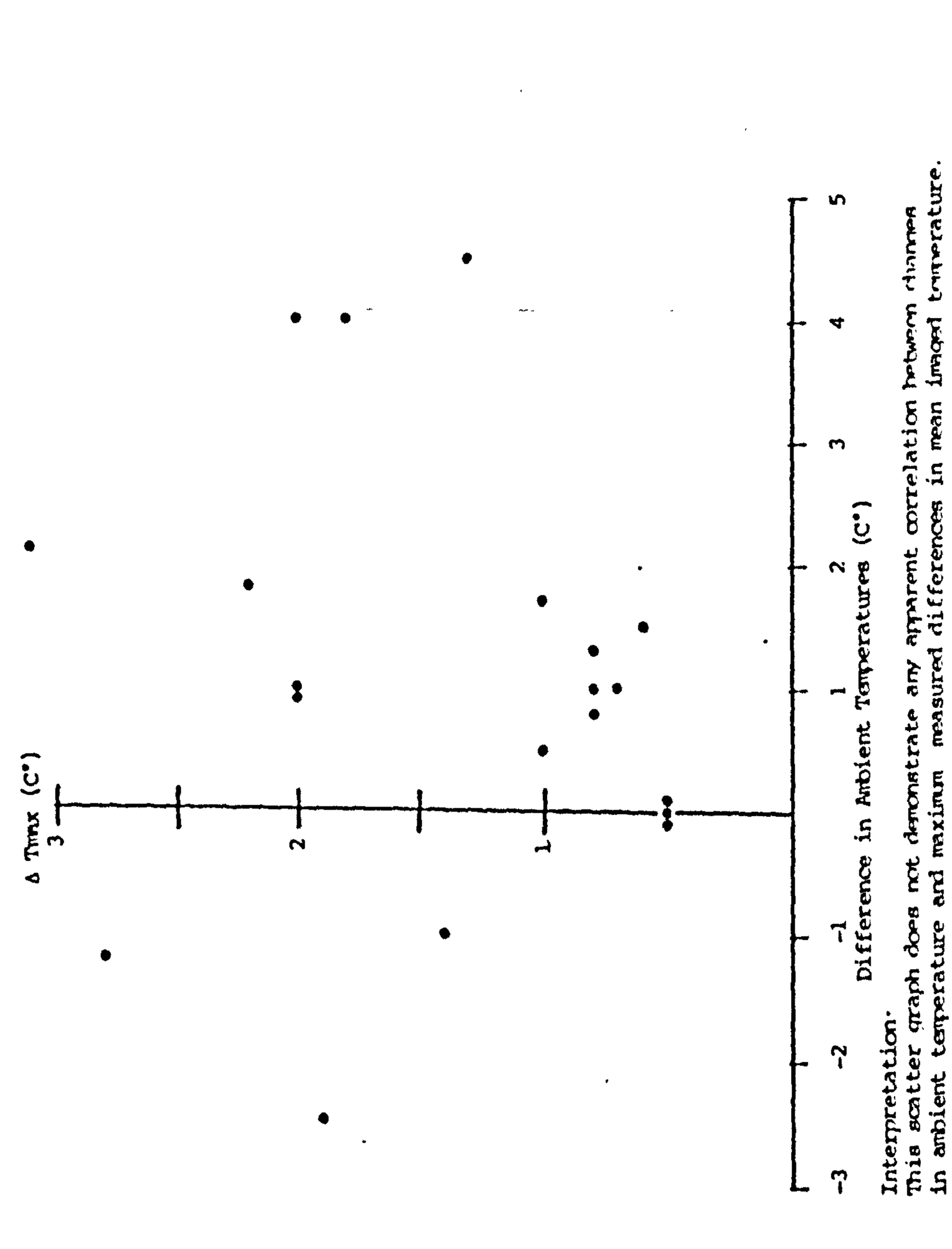
The average temperature ranges were calculated for each set of test conditions, ie, #1, "CCC", (as coded previously; one subject on the one seat for a given period of time). There were four groups of data (n = 4) satisfying these conditions, and having an average maximum mean imaged temperature difference of 0.8C°, and an average ambient temperature difference of +1.1C°. The ambient temperature differences were noted to determine whether or not they consistently correlated with the observed changes in average skin temperature. Although the average values were positive, there were exceptions with large negative ΔT_{amb} values weakening the probability that this was a source of interference.

The differences in ambient temperatures were plotted against the maximum variations in skin temperature to determine whether or not there was a correlation, see Figure 6.8 . There was a large scatter in the coordinates, with both positive and negative values, so that no pattern or specific relationship was evident.

6.3.3.3 influence of sitting time

The research subject (RR) had 3 trial sitting periods of approximately 6 hours duration on the Roho cushion, see Figure 6.9

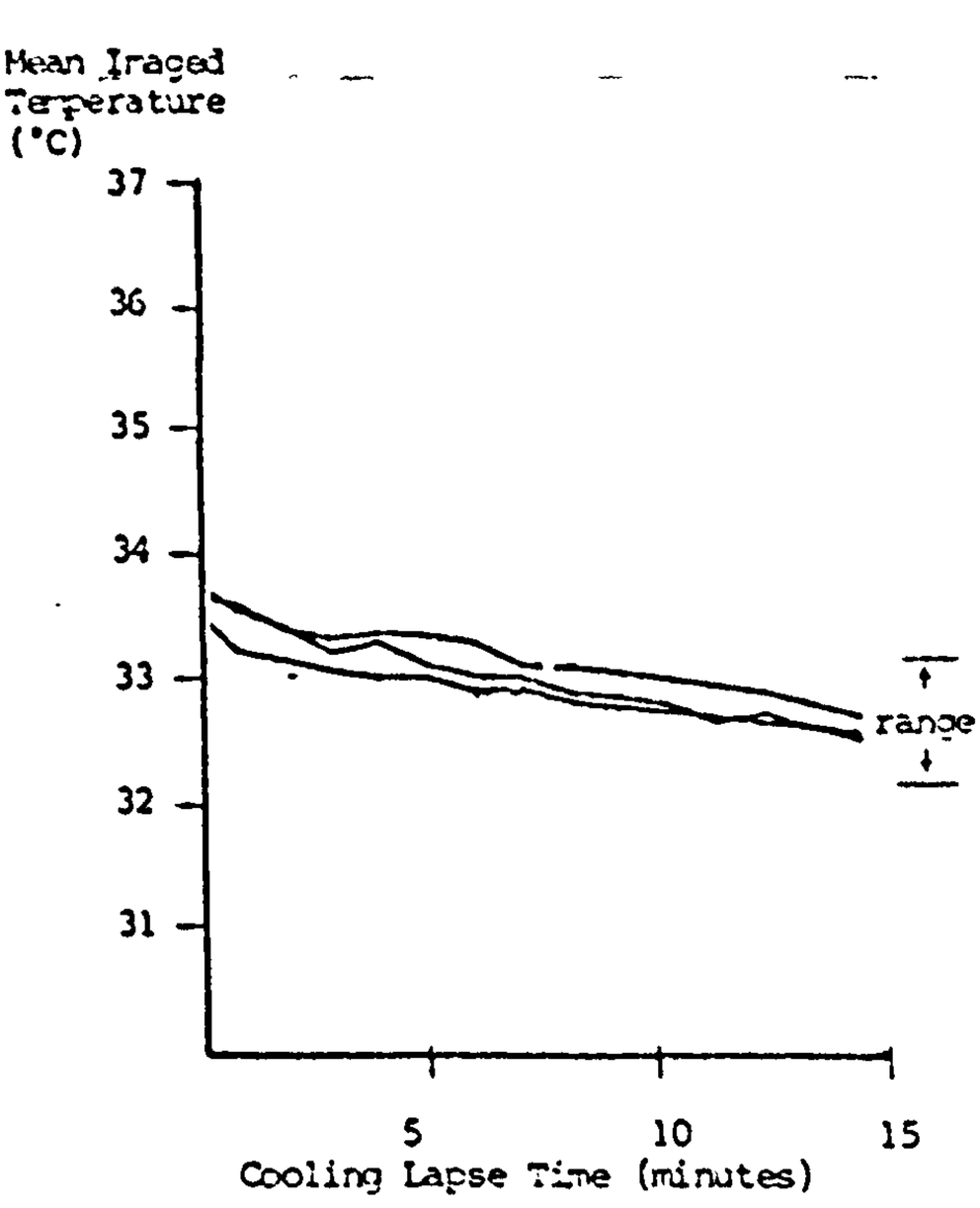
FIGURE 6.8 INFLUENCE OF AMBIENT TEMPERATURE ON MEAN IMAGED TEMPERATURE



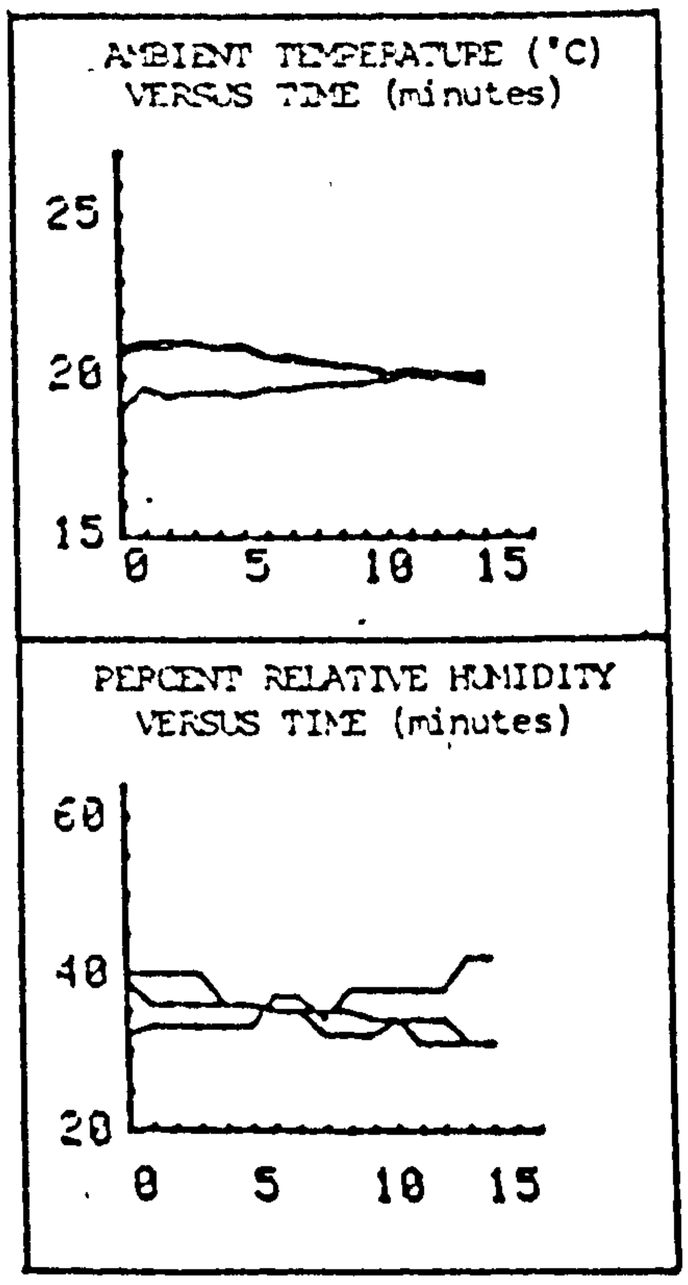
Interpretation:
This scatter graph does not demonstrate any apparent correlation between changes in ambient temperature and maximum measured differences in mean imaged temperature.

FIGURE 6.9 INTRASUBJECT VARIABILITY OF MEAN IMAGED TEMPERATURE - POST STRESS

(Subject RR - Roho Cushion - sitting 5-6 HRS.)



AMBIENT CONDITIONS



and 4 trials at different periods of duration on the same cushion, see Figure 6.10 . From visual inspection of these graphs changes in sitting time did not influence the skin temperature response and the variablity for these trials was less than 1C° for any given time sample.

6.3.3.4 influence of changes in seating systems

In a comparable series of trials the research subject sat on the gel, foam and Roho cushions for 5 hour periods on separate occasions, see Figure 6.11 . The cushions with insulating properties had similar cooling curves although the foam cushion had higher absolute temperatures (approximately +1.5 C°). In contrast the gel cushion had a more gradual increase in skin temperature (peaking after 10 min) suggestive either of higher pressures during loading or a change in vascular response induced by the cooler cushion. Further studies would be required to resolve this question.

6.3.3.5 intersubject variability

Subjects (CD-2, RR and TS) sat on Roho cushions for periods between 5 and 7 hours, see Figure 6.12 . The cooling rates appeared similar for RR and TS although the absolute temperature ranges differed by 1-1.5 C° . Subject CD-2 had a late start due to difficulty in positioning and a higher absolute temperature range than RR by approximately 2 C° . Subject CD-2 had a history of chronic tissue inflammation which possibly contributed to her elevated skin temperature.

FIGURE 6.10 INTRASUBJECT VARIABILITY - VARIABLE SITTING TIMES

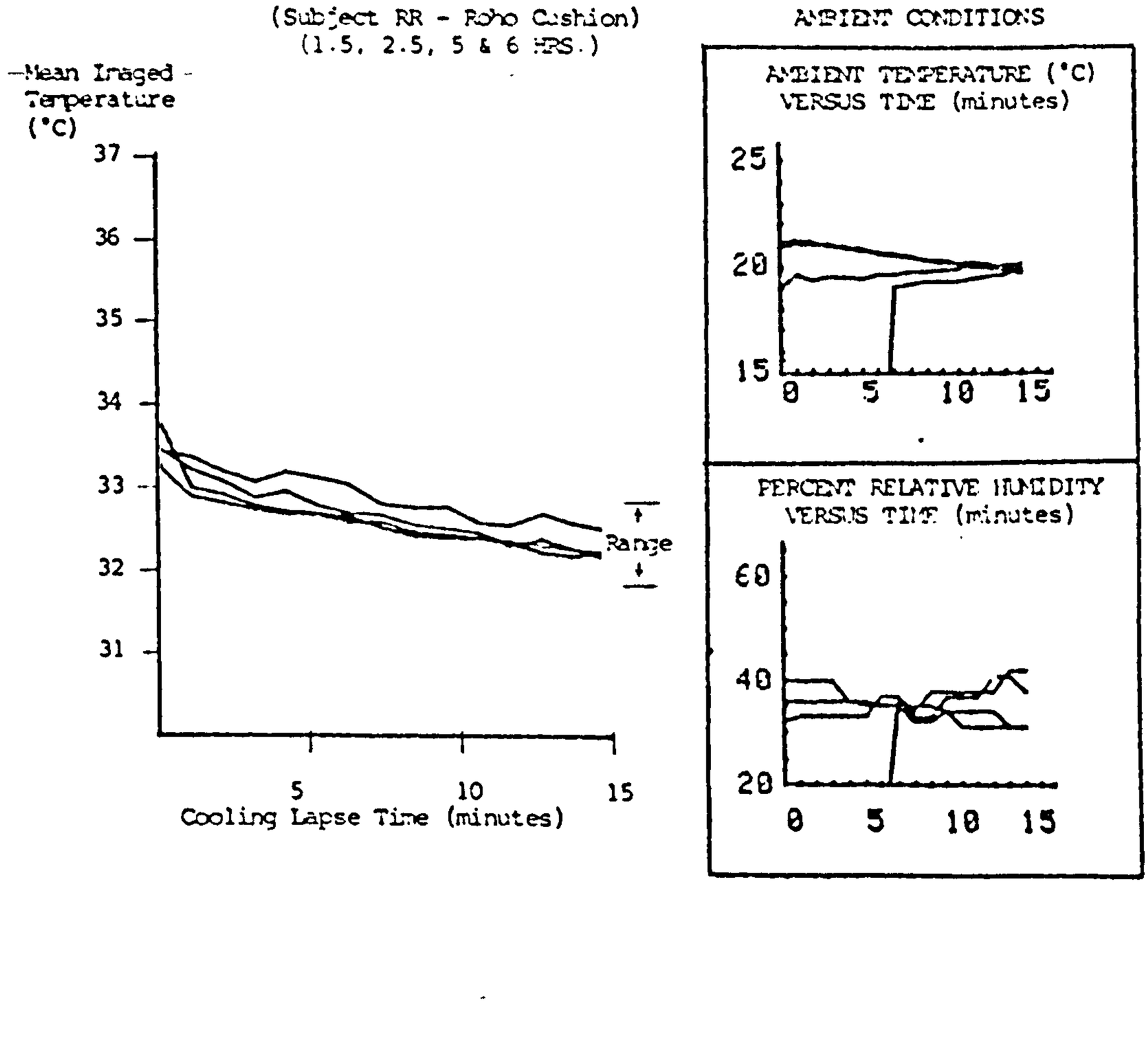


FIGURE 6.11 INTRASUBJECT VARIABILITY - VARIABLE CUSHIONS

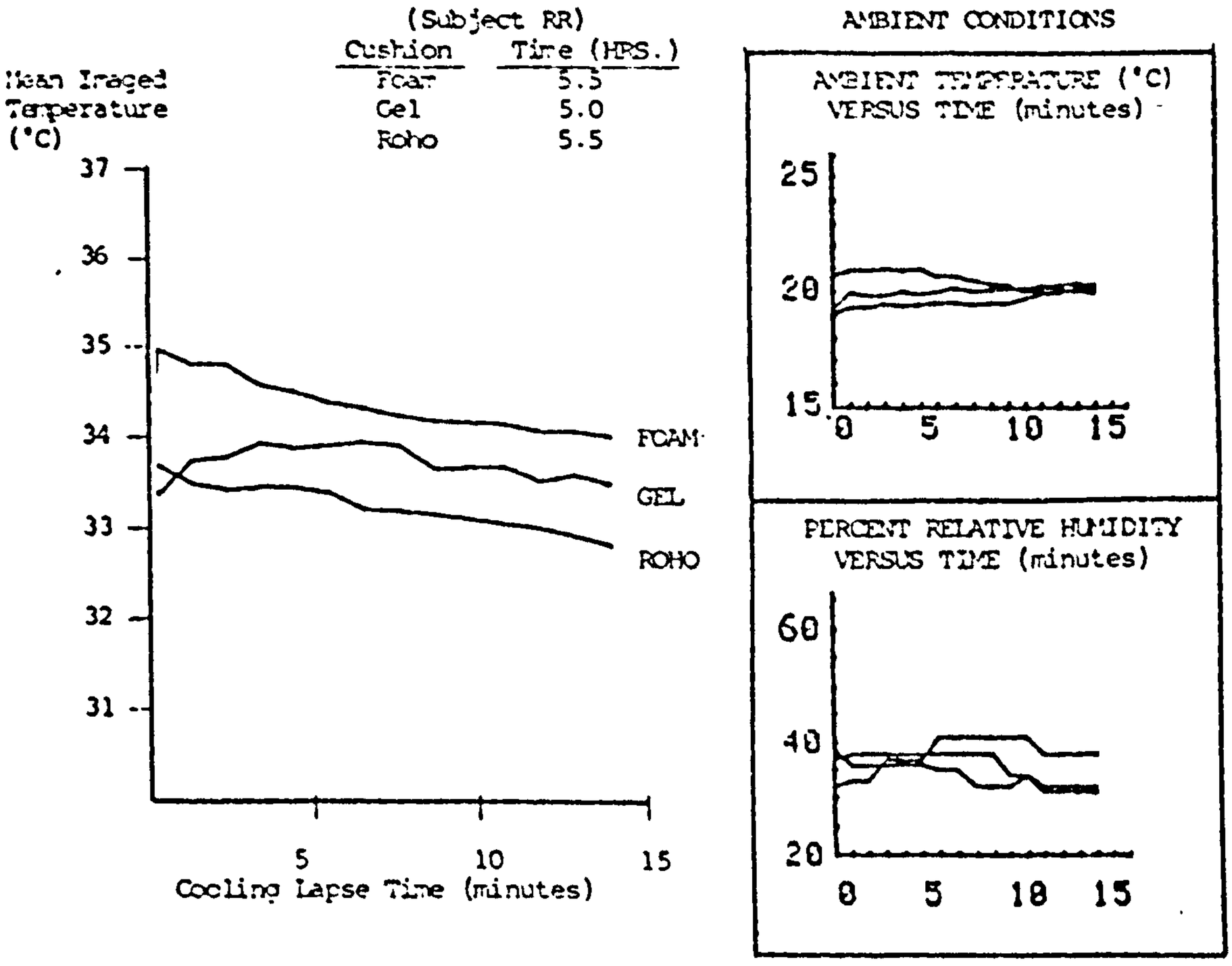
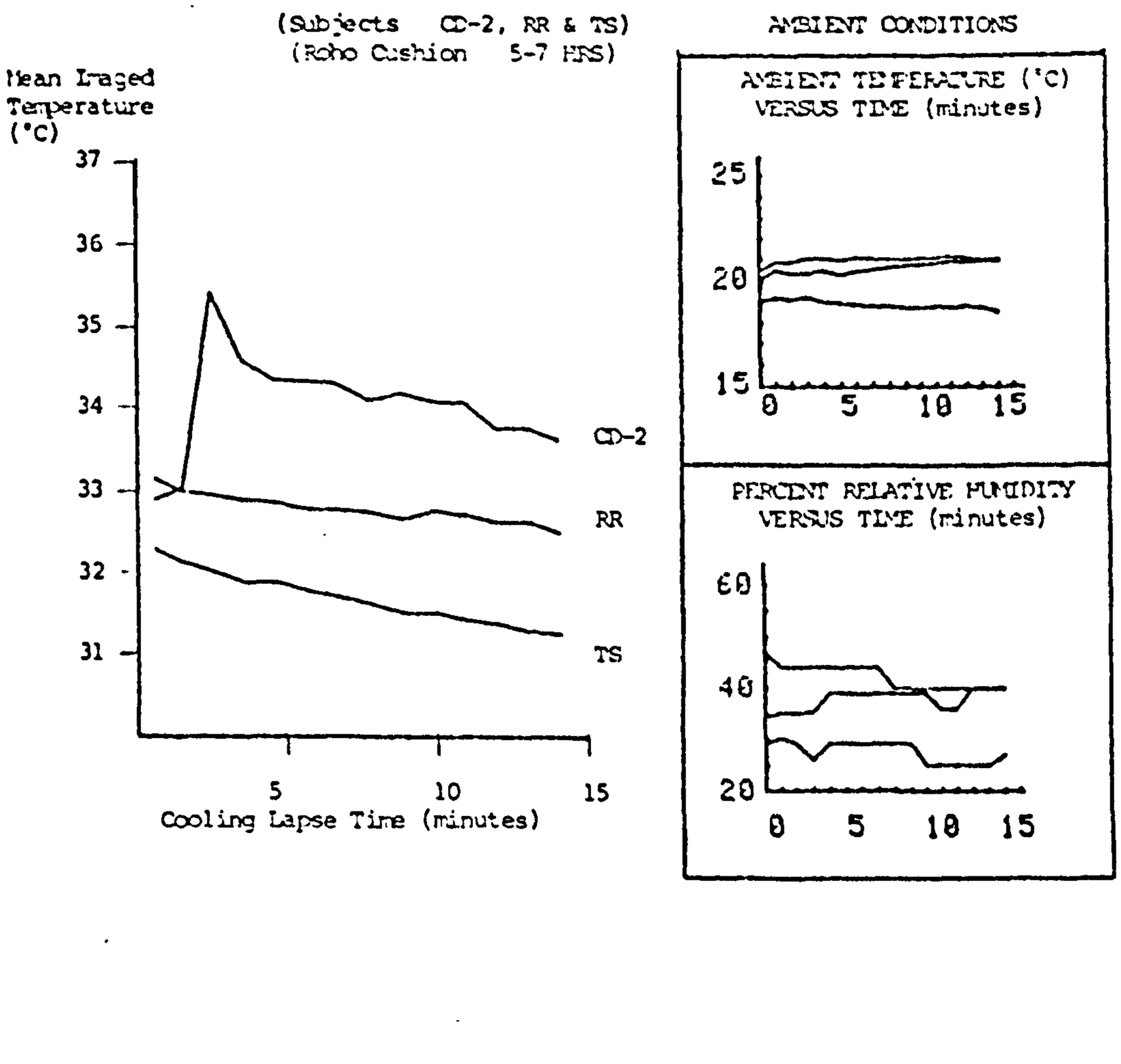


FIGURE 6.12 INTERSUBJECT VARIABILITY



The differences in these trials demonstrate that both the subject and the tissue quality need to be accounted for when intersubject comparisons are required.

6.3.4 K-Coefficient Comparisons

K-coefficient matricies were calculated to determine the distribution of modelled data. Scatter plots were generated for: (K_1 vs. K_2, see Figure 6.13), (K_2 vs. K_0, see Figure 6.14) and (K_1vs K_0, see Figure 6.15). The general distribution of these coefficients is summarized in Figure 6.16 to demonstrate the overall pattern. It appears that K_1 and K_2 are related by a linearly and hence a first order power fit may be an adequate model. Preliminary comparison of these coefficients by averaging demonstrated no significant trends. For this reason, it was felt that there was insufficient control over this clinical data to specify the best model and estimate ranges of confidence on the coefficients. This type of modelling would require exploration on animal models.

6.4 DISCUSSION

Chapter 6 described a number of contributions pertaining to the use of quantitative techniques with thermography in the context of studying a clinical problem. In addition, the results of the patient studies were presented. These developments and results are listed below:

1) A unique complement of thermographic instrumention was integrated for studying tissue trauma and seating in a clinical

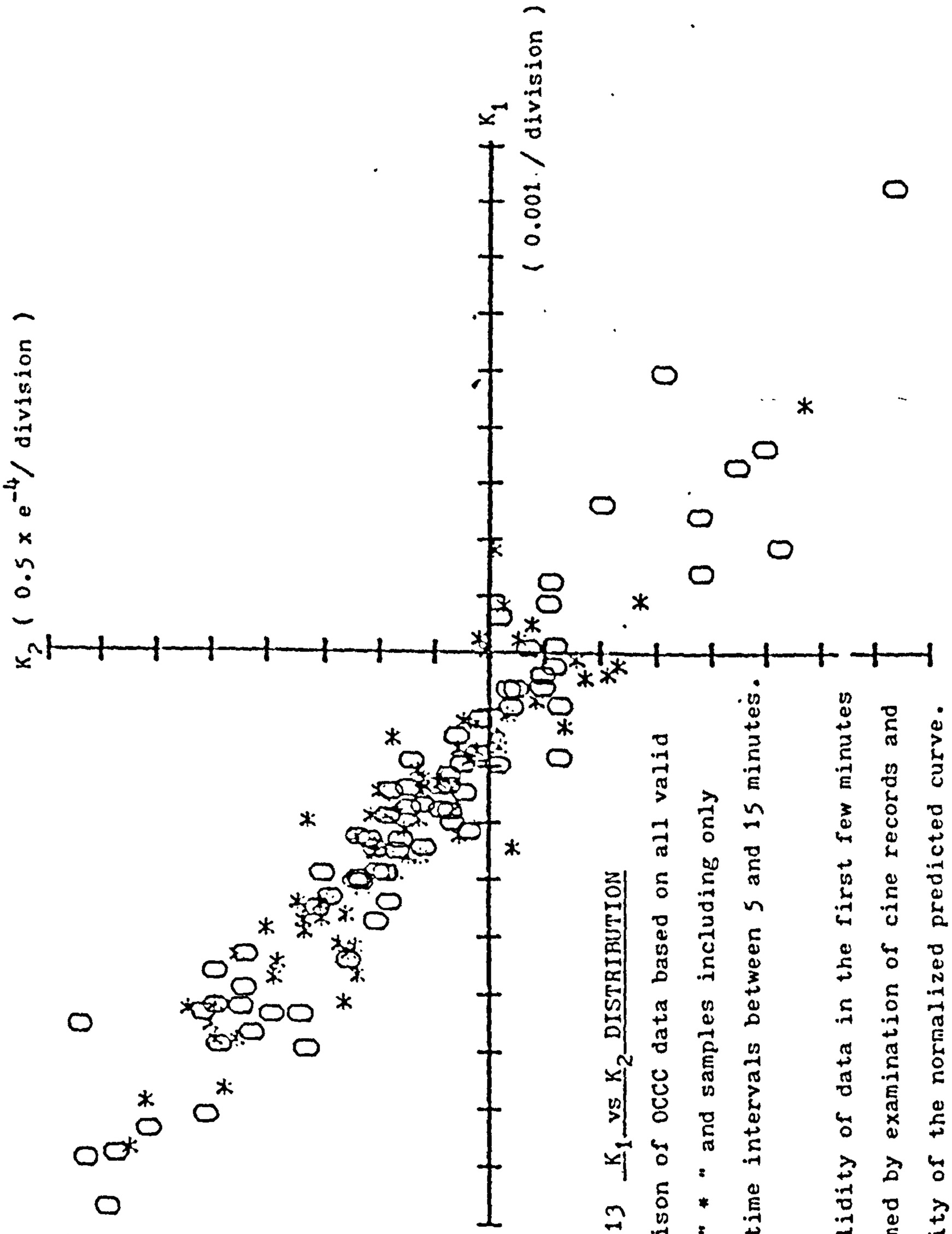


FIGURE 6.13 K_1 vs K_2 DISTRIBUTION

Comparison of OCCC data based on all valid data " * " and samples including only those time intervals between 5 and 15 minutes. The validity of data in the first few minutes confirmed by examination of cine records and stability of the normalized predicted curve.

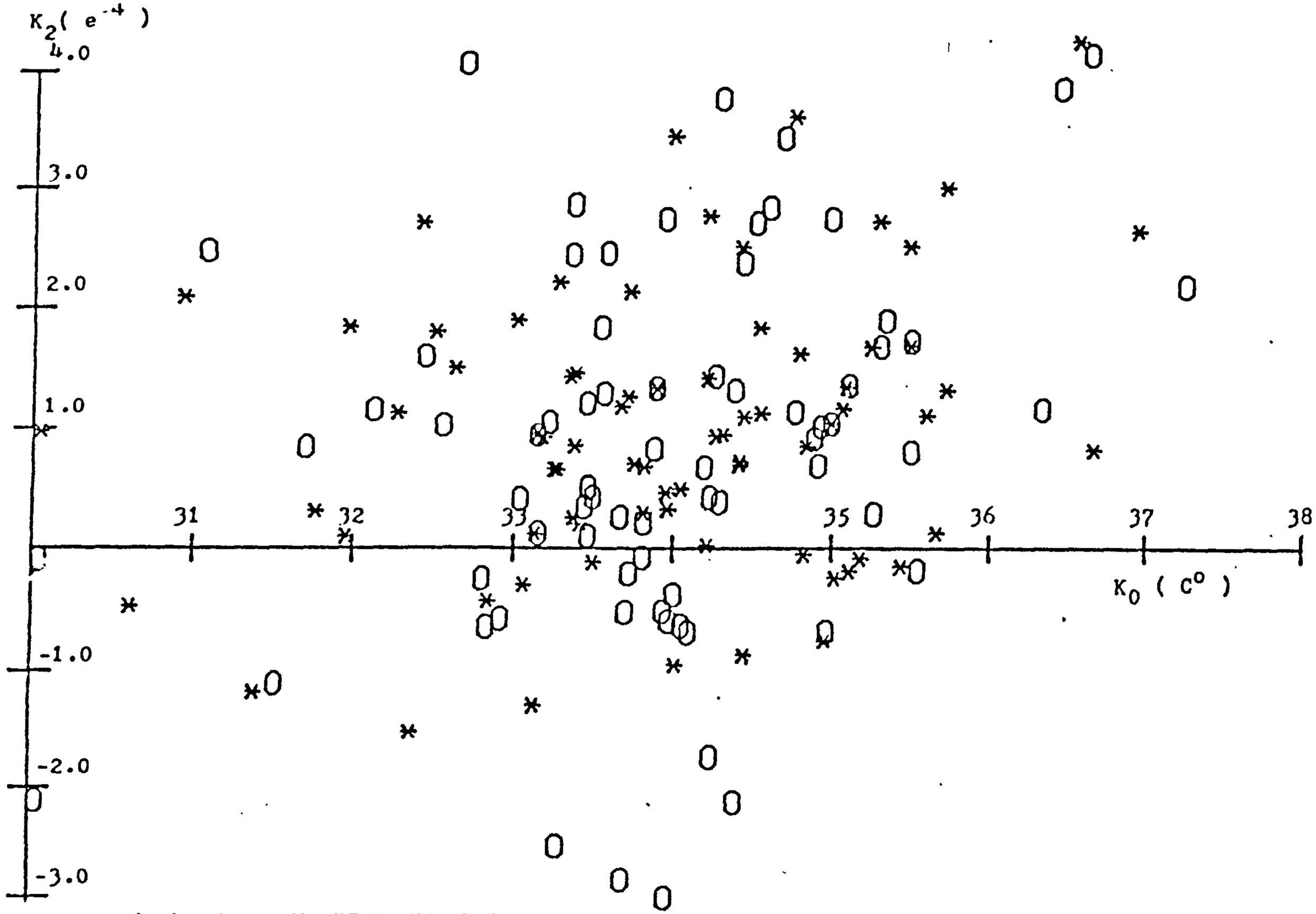


FIGURE 6.14 K_2 vs K_0 DISTRIBUTION *

OCCC DATA with " * " designating $\bar{T}$ calculations based on all valid data points and " O " calculated from samples between 5 and 15 minutes.

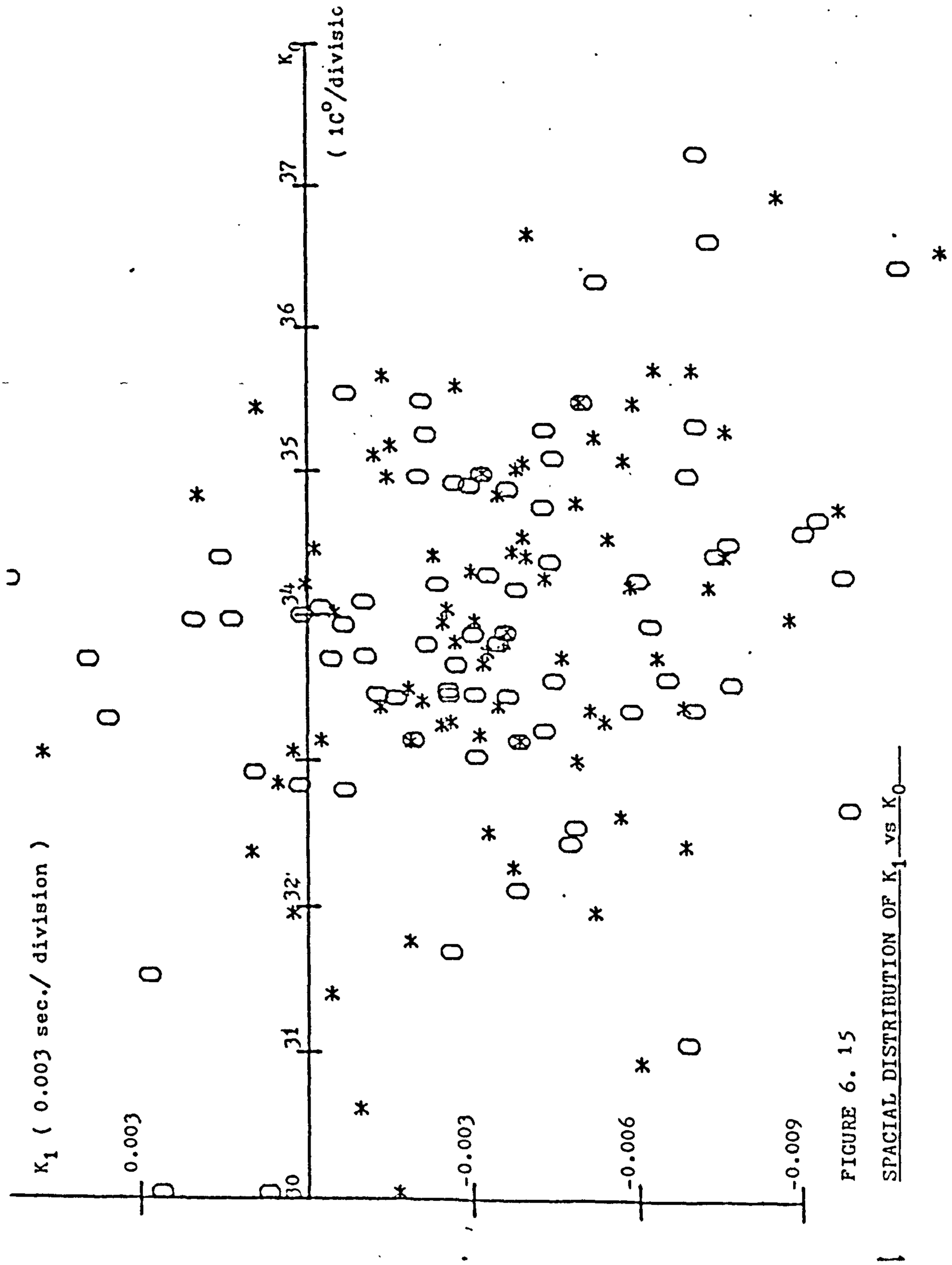


FIGURE 6. 15

SPACIAL DISTRIBUTION OF K_1 vs K_0

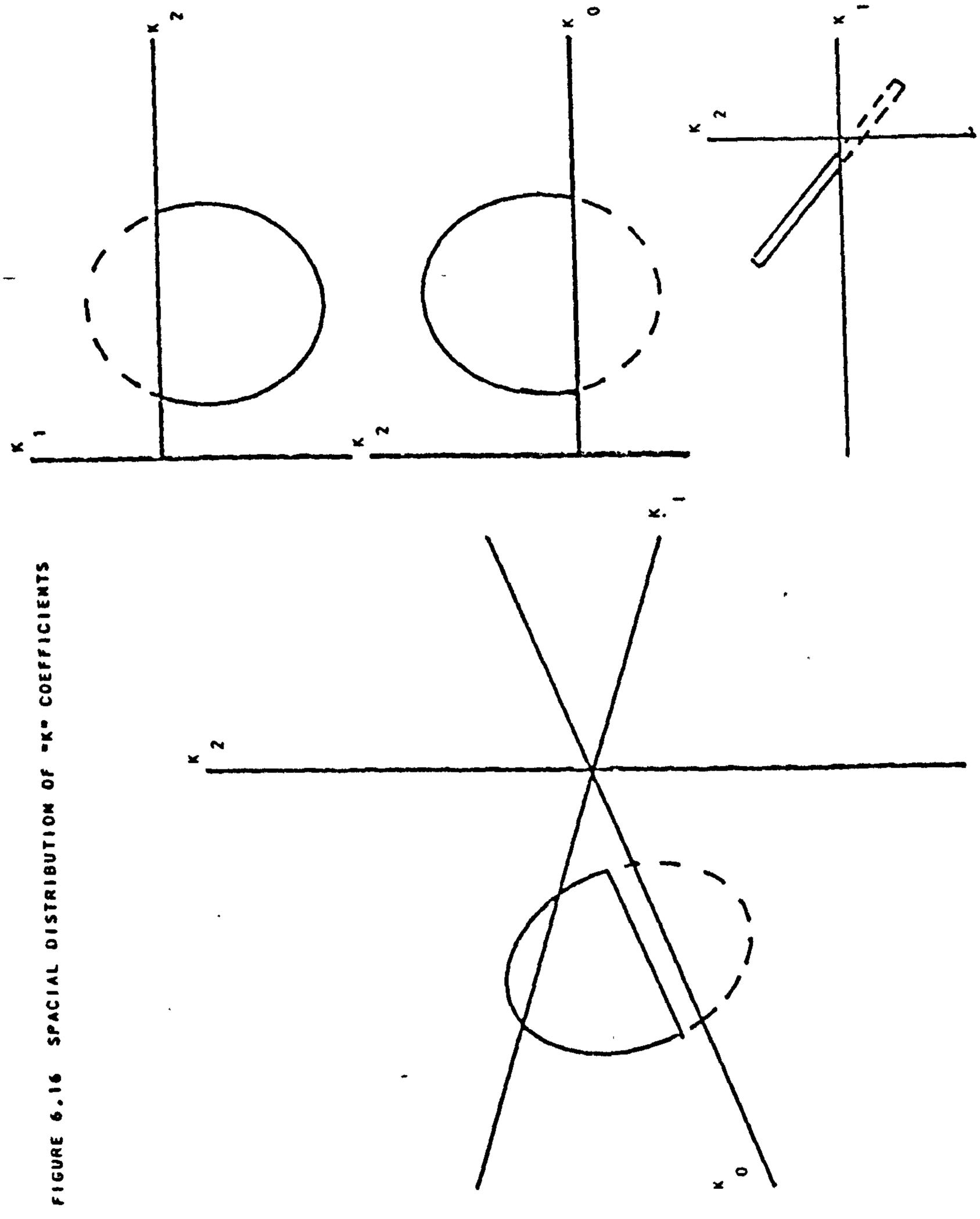


FIGURE 6.16 SPACIAL DISTRIBUTION OF "K" COEFFICIENTS

setting. The thermographic measurement systems included a timelapse cine camera, isotherm areameter, Tektronix microcomputer and multiplexer, and microfiche storage. This combination provided complete collection and documentation of continuous thermographic data .

2) Quantitative methods which were developed included the comparison of mean imaged temperatures sampled from localized high risk tissue sites. The analysis techniques consisted of comparisons of averaged sampled data, grouped to highlight the influence of the independent variables (subject, seat type and sitting time).

3) Modelling of the mean imaged temperature provided a means of reducing the data to several coefficients. The preliminary data were used in conjunction with a second order power fit and the scatter graphs of coefficients plotted against each other suggested the possibility of using a first order model. There was too much scatter in these preliminary data to warrant estimating the limits of confidence of averaged coefficients in a generalized model.

4) A selected case study demonstrated the sensitivity of such thermographic measurements to perturbations such as subject movement or poor data window positioning. However, it was also demonstrated that problem sites can be identified and recorded for reference in serial studies.

5) Although there was no correlation between the variations in ambient and skin temperatures; however, the large scatter of data

indicated the value of maintaining close control of ambient conditions.

6) The magnitude of baseline cooling over a ten minute period (5 to 15 minutes) was approximately the same for one or several subjects, T = 0.5 ±0.2C°.

7) There was no significant difference in mean temperatures comparing baseline and post sitting examples, until the sitting time was greater than 3.5 hours.

8) The variability of mean imaged temperatures was found not to be:

i) less than 1 C° when all the independent variables were constant;

ii) not dependent upon sitting time for subject RR on the Roho;

iii) influenced by cushion types with respect to both absolute temperature range and cooling rates; and

iv) strongly influenced by subject or tissue quality changes.

CHAPTER 7 DISCUSSION AND CONCLUSIONS

7.0 INTRODUCTION In this chapter the progression from clinical problem to research project is outlined, highlighting the rationale behind the choice of experimental techniques and methods. The findings are summarized and recommendations for further research discussed. The specific contributions of this research are presented, with respect to clinical thermography and pressure sore prevention.

7.1 EVOLUTION OF THE OCCC TISSUE TRAUMA PROGRAMME

7.1.1 Target Population and the Problem

The Tissue Trauma Programme at the OCCC was organized in response to the problem of persistent pressure sores identified in a number of patients with Spina Bifida. Pressure sore prevention was approached through a management programme which included patient education, training and protective seating.

Because both intrinsic and extrinsic factors contribute to the development of pressure sores, no one protective device or technique was expected to suit all patients. It was the philosophy of this programme to identify the special needs and limitations of each patient and select the most appropriate protective seating. Implicit in this approach is the requirement for objective evaluation of seating systems and selfcare regimens for each patient.

7.1.2 Seating Process

The provision of protective seating was based on a process cnsisting of the following steps: assessment, prescription, fabrication, and evaluation. Although much of this process remains

a clinical art, the research goal was to introduce scientific techniques which contributed to a systematic approach of seating selection.

One such technique, the measurement of pressure at the patient-cushion interface, has been presented by this author as a useful design tool in custom seat modifications; however, some pressure clinics have relied upon this for final evaluation. Further improvements in pressure transducer technology, which permit continual measurements over a large surface, would augment the utility of this approach. Eventually, when direct measures of the tissue's physiological activity are available, quantification of skin viability may be more feasible.

7.1.3 Evaluation by Thermography

Tissue blood flow has been considered one measure of tissue response which is proportional to the severity of induced ischaemia. Superficial blood flow increases local heat flux at the skin surface, and hence, the surface radiation detectable by such devices as thermographs. Deeper sites of ischaemia produce local increases in blood flow which, through conduction of additional heat to the surface, create a diffuse increase in surface temperature. Chronic tissue inflammation sustains increases in local blood flow and metabolism, with a resultant rise in superficial skin temperature independent of prior loading conditions. For these reasons, skin temperature was investigated as a measure of tissue tolerance. Thermography was chosen as a the most suitable temperature measurement tool to monitor tissue response to wheelchair sitting. The imaging of thermal patterns over large areas of skin made this technique clinically practical and accessible to automatic quantitative techniques.

7.2 THE DEVELOPMENT OF THERMOGRAPHY AS AN EVALUATIVE TOOL FOR WHEELCHAIR SEAT DESIGN

7.2.1 Previous Applications

In Chapter 3 it was shown that some correlation existed between the magnitude and duration of applied pressure and the subsequent rise and fall of skin temperature. A mathematical relationship for this correlation has not yet been derived, because of the multivariable nature of this biological system in which changes in skin temperature are only partially dependent upon the specific loading conditions. Other factors, such as the tissue quality, also have a critical influence on the physiologic response to stress.

A primary difficulty in all tissue trauma research is the indeterminate nature of tissue viability. With no direct measure of viability to serve as a frame of reference, other indirect measurements cannot be absolutely validated. Elevated local skin temperatures have been associated with tissue known to be healing, Barton (1973), or to be in an acute inflammatory state, Brand (1972, 1975) These gross descriptions of tissue condition do not predict the viability of the given tissues, but serve only as a classification of its present metabolic state. Interpretation of such measurements must be based on both reproducability and association with other relevant measures.

The first step in this process is the development of a method of applying the measurement system, so that the desired phenomenon may be observed consistently, and the data placed in an appropriate medium for further analysis.

7.2.2 Preliminary Approach

Thermography was introduced into the clinical setting with the initial goal of monitoring temperature changes in the buttocks before and after sitting. Each subject was his own control. This technique was maintained for all serial studies where possible and thermographic records were stored on microfiche to facilitate fast retrieval for direct visual comparison between examinations (a novel storage system which may be of benefit to other thermographic units). Early interpretation was based on the comparison of relative temperatures between known risk sites and healthy tissue in the immediate vicinity. Later, absolute temperature comparisons for the same site from one examination to another were of use where the sitting times and seating systems were comparable. This initial approach led the way to consideration of quantitative analysis techniques. It was hoped that greater specificity would be achieved, with the possibility of recognizing threatening tissue responses at an early stage.

7.2.3 Minimum Conditions for Quantitative Analysis

Because the changes in absolute temperature during cooling were small, isotherm areas were considered a better source of quantitative data. Initial tests in the environmental chamber at DCIEM studied the influence of changes in atmospheric parameters in order to determine the minimum conditions for reproducable quantitative studies. Subjects were tested on special seats producing high pressures over the ischial tuberosities. This model provided an opportunity to test the sensitivity of the measurement and analysis techniques.

Ambient temperature and relative humidity were varied to ascertain their influence on the quantitative data. These findings were then used in designing the thermographic chamber at OCCC.

7.2.4 Patient Trials

The quantitative techniques were then applied to individual case studies at OCCC and subsequently to a research subject over a two week period. Further refinement of the protocol and analysis continued during these tests. In summary, the area of risk had to be monitored with high resolution (0.5C°/div. sensitivity) and at minimum focal range to provide maximum resolution. Patients were more apt to shift position than were the experimental subjects during examination, introducing artifacts into the data. Hip blocks were used to minimize this effect at the cost of increased set-up time and loss of initial cooling data. Altered cooling responses such as prolonged heating resulting from acute inflammation were measureable without the data from the first two minutes.

Both accumulated isotherm area and mean imaged temperature versus time plots were used to obtain comparative response of high risk tissue sites to prior loading. Further analysis of the mean imaged temperature data was attemped through curve fitting and calculation of coefficients for a second order power fit model. It was assumed that the cooling process would be exponential, as predicted by Newton's Law of Cooling, but modified by physiological phenomena, such as local heating from increased blood flow or metabolic activity.

7.3 DISCUSSION OF FINDINGS

7.3.1 Interpretation of Thermographs

Thermographic data were measured from microfiche files and compared with tissue quality gradings based upon photographic skin tone records. The reason for this comparison was two-fold. First, it was thought to be useful in determining whether or not these clinical tissue assessment techniques corresponded to maximum temperature data, and second, if these temperature measurements could be used to form interpretation guidelines based upon the clinical practice at OCCC.

The maximum temperature data were found to fall in a wide range when plotted against the tissue quality parameters. A weak trend of increasing maximum temperature with increasing severity of tissue condition was noted. Tissue known to be inflamed in the presence of an open lesion, was found to be in excess of 34°C, by greater than one standard deviation under all test conditions, while tissue graded in good condition was at a temperature of less than 34.5C°. This suggested that tissue at 35C° falls within a warning zone, and at 35.5 - 36C°, outside of the good tissue range at the 95% level of confidence.

Under the experimental conditions defined in Chapter 6, skin temperature between 34 - 35°C was used to indicate the need for further studies to detect any progression of change. Temperatures in excess of 35.5 °C signalled the need for extensive pressure relief to permit tissue recovery.

A correlation analysis was used to compare groupings of sitting times. Four groups of sitting conditions were imposed, (all of the samples, baselines only, all seating trials and groups of seats without the baselines).

The Pearson correlation was used to determine whether or not any linear correlation might exist and, if so, to estimate the level of confidence and sign of that relationship. The interdependence of any two parameters was calculated as a percentage, based on the square of the "r" value.

There were no strong correlations with the sitting times, although the selection for subjects without any seating system and those with the bean bag seats had time-maximum temperature interdependence of 15% and 31% respectively. Since both these seating arrangements had, through clinical experience, frequently led to further tissue trauma, this type of correlation might provide a means for evaluating seating systems with simple measurement tools. If there is a strong correlation between the duration of sitting time and the persistence of elevated skin temperature, no steady state level of tissue stress has been reached. If, theoretically, a seating system has a sufficiently low pressure or permits adequate pressure relief, such that there is no accummulative effect during prolonged sitting, any linear approximation between sitting time and peak temperature would have zero slope.

The maximum temperatures were also plotted as relative temperatures, (the maximum temperature at a sample site minus the temperature of the coolest site for that examination), to determine whether or not there were stable temperature patterns for a given subject and/or seating system. The same correlation analysis was used to detect interdependence between relative skin temperature and sitting time.

Relative temperature differences of up to 2.5C° were found within the range of good tissue at the 68% confidence limit. This

value corresponds with the relative increase in temperature found around healing lesions by Barton (1975). Open lesions ranged up to +6C°, and inflamed tissues to +5C°. The correlation analysis showed similar, but weaker trends, than those obtained by using the absolute temperature.

In summary, this review of the thermographic files demonstrated that there was considerable variability in data obtained by visual interpretation. There appeared to be a warning zone which could have clinical application, beginning at 34.5C°, with a further warning at 35.5C°. Although these ranges would be shifted, were the examination conducted in a cooler or warmer atmosphere, such warning zones could be established for screening activities.

7.3.2 Environmental Trials

Since tissue reacts dynamically to external pressure, time dependent measurements were thought to be necessary to describe tissue quality. The time-lapse recording of thermographs, reviewed on an optical analyser, permitted observation of changing thermal patterns at either compressed or expanded rates. Slow differential cooling was apparent during high speed viewing, with rapid changes detectable in the single frame mode. This technique might be of value in other applications of thermography where the important time dependent features have not been identified.

The thermograph displays skin temperature in step changes, with a magnitude determined by the sensitivity of the camera. The area of skin within any particular temperature band changes continuously and, as such, can be measured with more resolution than the peak temperature within the same area of skin.

Isotherm area measurements were sufficiently sensitive to detect hyperthermic responses, as reported in the literature, Rogers (1973) and Roemer (1978). Peak temperatures were observed several minutes after application of pressure sufficient to induce reactive hyperaemia. In agreement with the above studies, it was found that the more intense the pressure, or the greater its duration, the more persistent was the hyperthermic reaction. No specific definition of this relationship was developed, as ischaemic conditions are difficult to model. In these experiments, the pressures were in excess of the measureable range available with the inflatable pneumatic sensors, and the focal point of maximum pressure was difficult to isolate as it moved with small changes in body position.

All research in the tissue trauma field must contend with the lack of an absolute measure of tissue viability. An alternative approach requires comparison of measured reactions of tissue known to be healthy, with that of tissue in a pathological state. Generally speaking, the persistence of high temperatures would appear to be the first characteristic for detailed study. The accumulated isotherm area versus time plots were the most sensitive to hyperthermic responses; however, quantitative comparisons of mean imaged temperatures at the higher ambient temperature also reflected hyperthermic activity. It was considered necessary to reduce the data sampling window such that it only enclosed the area of interest to improve this sensitivity.

Tests at various ambient temperatures showed no apparent masking of the cooling response, although hyperthermic responses were prolonged at ambient temperatures greater than 21°C. Fluctuations in ambient temperature introduced oscillations into the

areameter data which interfered with their interpretation. This indicated that stable ambient temperature was required, estimated at $\pm$ 0.5C°.

Step changes in relative humidity of 10% - 15% did not introduce the same magnitude of interference noted with changes in ambient temperature fluctuations. Draughts were minimized to permit uniform cooling of the skin. Although no formal studies were made of this influence asymmetrical air currents would introduct similar changes in surface convective cooling.

The guidelines for environmental stability were assessed on the conservative side for the design of the clinical examination room at ±0.5C° and at ± 10% R.H. It was clear however, that monitoring systems were required to integrate measurements of the ambient conditions into the data collection system to provide a time sequenced record of any environmental disturbances.

7.3.3 Patient Studies

There were three phases to this part of the research: preliminary patient studies, to develop the OCCC system and protocol; secondary intensive patient studies, to develop the analytic techniques; and finally, research trials, to assess intrasubject variability of quantitative thermographic parameters.

One case study was reported in detail to demonstrate the range of applications required with respect to varying tissue conditions and seating needs. Some of the practical problems associated with patient studies, such as subject movement, were described as they were accomodated in the research protocol. It was determined that small data windows (less than 20% of the view) should be used in such studies to increase the sensitivity of the measurement, and

also that hip blocks are required to stabalize the subject. Adhesive foil markers were used to provide anatomical references from examination to examination.

The real-time areameter displays for these initial studies were the same as those developed during the environmental trials, (percent accumulated isotherm area and mean imaged temperature versus time). Hyperthermic changes or delayed cooling were readily perceived by the former display but further compression of the data was obtained using the latter for comparative analyses.

Both computations of averaged mean imaged temperatures at sampled time intervals and K-coefficients for second order power fit polynomials were used to test the sensitivity of the quantitative data to the independent variables of sitting time, subject, and seat type.

Mean imaged temperature parameters were sensititive to changes in seat type when the sitting times were in excess of 3.5 hours. There was too much variability in the average temperature data to reliably distinguish between short sitting times and baseline examinations. Small sample sizes were the result of the large number of independent variables which were minimized with the experiments involving the experimental subject.

When all independent variables were kept constant the variability was less than 1C°. Intersubject variability was associated with the greatest differences in mean imaged temperatures; however, it was not possible to distinguish between tissue quality changes and systemic subject variations. Variations in seating systems for the experimental subject resulted in changes of both the absolute temperature and cooling pattern. The

thermodynamics of specific cushions during loading were thought to have an influence on the subsequent temperature response after pressure relief.

When the amount of skin cooling was used as a measure of stress response ($\Delta\bar{T}_{5\text{-}15\ min.}$); it was not possible to distinguish between a low level of stress on healthy tissues and hot inflammed tissues, neither of which cool markedly on exposure to ambient conditions. Additional data is required to reference the absolute temperature range.

Curve fitting techniques were used to further compress the data, while retaining information describing the shape of the cooling curve and intercept values representing the temperature range. The quadratic semilog model was chosen as a model for the cooling curves as described by tissue polynomial "K"coefficients. All of the K-coefficients were plotted against each other and a linear relationship was found between the K_1 and K_2coeffients. This result inferred that a simpler linear model could be used by substitution of K_1 or K_2. The small sample sizes resulted in large standard deviations, which did not provide a useful basis for data comparison with the small sample size available.

7.4 FUTURE DIRECTIONS

7.4.1 General Priorities in Tissue Trauma Research

One objective of this programme was to apply research techniques in the provision of protective seating. As a result, experience was gained in technology transfer with respect to clinical practice. In addition, it was possible to gauge the unmet needs from a clinical perspective. In most treatment centres, the

level of pressure sore awareness has been too low to anticipate a broadbased understanding of the principles of pressure sore prevention although this situation is improving. The identification of critical intrinsic and extrinsic risk factors for individual patients demand this understanding. Improved education must be the starting point to achieve any impact on the incidence of this problem. Such educational material should be prepared with the use of audio-visual aids to reach both patient and family.

Basic biomechanics research into modelling of the transfer of load to flesh should provide design guidelines for the seating industry. However, it is unlikely that pressure measurements alone will suffice to predict the pressure sore risk for an individual patient. This field of study will improve as techniques become available to register interface pressures over an area, continuously for a prolonged period of time. Such research would link biomechanical and behavioural engineering, relating body movements with changes in local tissue pressure.

Further work is required to identify absolute measures of tissue health which in turn could be used to calibrate indirect measures such as thermography. Such a direct measure of tissue viability would not have to be compatible with clinical practice, if correlations could be established with alternate measures.

Currently available seating systems can provide a good level of protection for most compliant and well motivated patients. Nevertheless, there remain a number of high risk individuals, for whom recurrent pressure sores continue to be a threat. Some of these patients present with severe orthopaedic deformities and extremely poor weightbearing tissues. For this group, prolonged

sitting remains a life-threatening risk. Others are not compliant with self care routines, and in this sense, have not accepted responsibility for their own care. For those with good cognitive abilities, this may reflect upon the rehabilitation programme, or the manner in which it is presented. It may also be indicative of psychological issues not yet adequately resolved.

There is a need for further research into warning systems, either of the type responding to sitting behaviour, or those which provide non- contingent reminders. Both types will be most successful if designed as potential prosthetic aids and not merely for training purposes. Because one of the prime intrinsic risk factors is the loss of sensation in the tissues, such aids may offer a the potential replacement.

Thermography is an example of an instrumentation technique which can integrate tissue quality information into the seating design process. Pressure measurements provide design information based on the biomechanics of the patient and the support surface neccessary for seat fitting. Seating programmes will need to adapt this approach of integrating measurement systems into the fabrication and selection process to meet the varied needs of high risk patients.

Further specificity could be obtained in thermographic interpretation if high resolution off-line analysis were possible. In this mode, temperature changes at identified high risk sites could be tracked without sacrificing the isotherm pattern information for the full sitting surface. The hardware required to facilitate this type of analysis is presently reaching the market through the advent of scan converters which make thermograph data compatible with standard video image analysis equipment.

7.4.2 Application of Research Findings to Seating

During the research project it became evident that the provision of seating was a systematic process involving the following steps: patient assessment, seating prescription, seat fabrication, evaluation and long term review. From this process, it can be seen that the initial assessment must delineate specific risk factors for the individual. These factors included both physical and psycho-social aspects, which can be ranked to provide a priority problem list to assist in defining the prescription. Although this routine has not been computerized, the approach does opens such possibilities, because a priorized problem list could be converted into a set of design criteria for a rationalization of seating selection.

A seating system is comprised of a weightbearing support surface, and when appropriate, some form of trunk support. Thermography was used primarily to study the consequences of individual subjects using specified or experimental weight-bearing cushions. The most generally useful device for high risk patients was found to be the Roho cushion. It's drawbacks related to sitting stability, cost and maintenance. Nevertheless, it appeared to achieve the best pressure distribution and cooling responses. The foam cushions were mostly constructed of Temper-Foam and polyurethane foam. These were found to be adequate for young patients, when used in conjunction with a plywood base.

The high level of mobility and low pressure levels associated with children made this simple seating practical. Contoured polyurethane foam cushions were used occasionally for sacral and coccygeal relief and harder custom contoured Temper-Foam cushions

for subjects requiring a high degree of stability and having good tissues overlying bony prominences.

These seating systems are described in more detail in Appendix II. However, there remain many opportunities for the development of better support systems, particularly for the elderly and immobile. Such research will require the design of systems which integrate seating surface and mobility base facilitating changes of position and hence weightbearing.

7.4.3 Thermography: Its Possibilities

Thermography can be further developed as an evaluative tool in itself, but can also can lead to more precise use of simpler thermal measurement systems. The effective use of spot temperature detection will be enhanced by increased understanding of dynamic surface temperature changes, readily studied by quantitative thermography. Time lapse filming can be used to provide insights into new thermographic applications prior to the use of quantitative techniques.

The DCIEM areameter was a preliminary analytical tool which appeared to be useful in characterizing local skin temperature changes. There may be other circumstances in which temperature gradient measurements such as that available to the Spectrotherm system, might prove to be the most sensitive technique. Quantitative analysis is becoming more powerful with improved techniques in the instrumentation associated with the newer thermographic systems. However, the widespread use of thermography will depend upon the reduction in capital cost of the equipment. If vidicon or solid

state systems are successfully developed, eliminating the need for the expensive mechanical scanning components, such a price break might occur.

In the present state of development there should remain several seating centres conducting research using thermography to develop guidelines for the application of simpler devices, such as non-contact radiometers, and to enhance the research design of seating systems. Large scale studies should include a battery of evaluative tools to classify sitters by behavioural and biomechanical criteria. Such a programme should make use of movement counters, interface pressure measurements (matrix if possible), humidial sensors and thermography. Tissue classification techniques should also be refined to cross-relate the results with common clinical practice, (the development of skin quality testing).

7.5 A SUMMARY OF THE AUTHOR'S CONTRIBUTION

7.5.1 Development of the Tissue Trauma Programme

a) A comprehensive base of relavant literature was prepared for use in the patient teaching programmes at OCCC.

b) An engineering role was evolved in the Tissue Trauma clinic through the introduction of measurement techniques such as pneumatic pressure transducers, body movement counters and thermography.

d) Custom and research seating systems were introduced in response to problems recognized for individuals or groups of patients.

7.5.2 Development of Thermographic Techniques

a) Specific protocols for examining seating patients were developed by the author, (i.e., sequencing of events during the examination, and critical sites and temperature ranges involved).

b) The combination of time-lapse and quantitative techniques had not been previously reported in the literature. This includes the use of the adapted cine-camera and the application of an areameter to study area isotherm changes during a cooling response.

c) The thermograph storage system employing microfiche film, facilitated the review process and produced a uniquely compact thermographic file.

7.5.3 Finding of the Thermographic Studies

a) Persistent high temperatures can be used as a guide in seat modification.

b) Persistent temperatures over 35.5C° were associated with tissue damage as evidenced through clinical examination.

c) Healthy tissues were found to be below 34.5C°, at a 65% confidence level.

d) The measurement of absolute temperatures from thermographs demonstrated the need to control such parameters as tissue type and condition, sitting time and seating system. However, when all the independent variables were constant the variability for healthy tissues was found to be 1.0 ± 1C°.

e) The minimum environmental conditions required for reproducible thermographs, in association with quantitative measurements were; to be ambient temperature fluctuations of less than ±0.5C°; relative humidity fluctuations of less than ± 10% and; draughts less than 1 foot per minute.

f) Quantitative data were displayed as an accumulated area plot versus time beginning with the highest temperature channel. This emphasized hyperthermic activity by introducing a concave downwards family of curves.

g) The areameter had to be used at its minimum range to achieve adequate sensitivity, (with a data window area of less than 20% of the field of view). This high sensitivity necessitated stabilization of the subject with hip blocks.

h) Mean imaged temperature loci produced a compressed display of the data and curve fitting techniques provide an opportunity of characterizing the cooling response by calculating polynomial coefficients. The quadratic power fit model was analysed, however; further research would be required to established confidence limits on coefficients for such models.

i) The coefficients of this quadratic expression fell within a definable pattern when plotted as a three dimensional scatter graph with axis K_0, K_1, K_2. A linear relationship was observed between coefficients K_1 and K_2. This indicated that a simpler, two coefficient could be used.

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APPENDIX I TABLES

Two sets of tables are presented which support arguments relating to patient assessment and one table which lists the patients and examinations which was the source of quantitative thermographic data.

A) Intrinsic Factors Contributing to Pressure Sores

The risk factors are categorized and example situations described to emphasize the variety of dangerous situations which commonly arise for individual patients.

B) Extrinsic Factors Contributing to Pressure Sores

This table is similar in structure to that developed for the intrinsic risk factors.

C) Study Population

The subjects for whom quantitative data was obtained have been listed. Codes were used based on the patient's initials toidentify them in the text. This table also includes data pertaining to their age, sex, tissue site quality, referral reason and sitting conditions.

INTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

	FACTOR/CATEGORY	SIGNIFICANCE
I M M O B I L I T Y	BEDRIDDEN	*Patients who are bedridden without the capability of moving themselves are dependent upon others move them frequently enough to prevent pressure sore development.This is unreliable for chronic care patients.
	WHEELCHAIR BOUND	*These patients spend prolonged periods of time sitting with a large proportion of their weight passing through a small area.It is difficult for this group of people to maintain a rigid routine of regular pressure relief while functioning in an able-bodied environment.
	AMBULATORY	*There are some patients with low levels of spinal cord lesion who are ambulatory,often with a great expenditure of energy,and consequently will sit on regular furniture.Unfortunately many of these people will also have insensitive skin over their ischial tuberosities and loose the protection which can be obtained from protective seating.
A N A T O M Y	ORTHOPAEDIC DEFORMITY	*Severe spinal and/or lower extremity deformities may reduce a person's ability to shift his weight or to move within their support surface. This then has the effect of reducing their mobility and oportunities to relieve local ischaemia.In addition such deformities may also produce assymetrical weightbearing and increase localized pressures under bony prominences.
	TISSUE STRUCTURE	*Subjects who have had a prior history of tissue trauma will likely have lost pressure distributing tissues through atrophy or surgery.This will produce higher pressures in the residual supporting tissues.In addition previous trauma may compromise the quality of the local stuctures by the presence of bursas,scar tissue and possibly compromised local circulation.
	TISSUE HEALTH	*Tissue subjected to repetative loading and ischaemia is apt to become inflammed,Brand(1971), and subsequently at greater risk if ischaemia is induced in this state.Therefore the risk of pathology is dependent both upon fixed anatomical factors and time dependent changes.For this reason it becomes difficult to generalize on the safety of support systems.

INTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

	FACTOR/CATEGORY	SIGNIFICANCE
NEUROLOGY	SENSORY LOSS	*Skin sensation provides feedback to the central nervous system during the early phases of ischaemia.This is interpreted as discomfort one moves in response to relieve the distressed tissues.This protect ,if lost or impaired by a sensory deficit,may result in an abnormal sitting behaviour characterised by prolonged immobility and severe ischaemia.
	SPASTICITY	*Increased muscle tone in the lower extremities may impair a patient's sitting balance and tend to increase in-plane forces if;for example,he has tight hamstring muscles.Assymmetric trunk muscle tone may produce assymmetrical weight bearing and lead to a permanent spinal deformity.This type of risk can in some cases be modified by drug treatment or surgery.
	DEINNERVATION OF ORGANS	*The most common risk faced by the spinal cord injured patient is loss of bowel and bladder function.This may lead to urinary incontinence with the need for special management techniques. If the patient is unsuccessful in gaining control he may become chronically wet and the risk of tissue maceration or chemical scalding is present.
MEDICAL	NUTRITION	*Patients with either a general or specific nutritional deficit will have a reduced ability to offset edema or infection,Schell(1966).In particular low protien and ascorbic acid levels have been found to coincide with increased pressure sore risk.
	DISEASE PROCESSES	*Cancer and Diabetes are two examples of diseases which can directly increase the risk of pressure sores.In these circumstances the prevention of this secondary complication may be as dependent upon the progress of the primary disability as the design of any support surface.
	INFECTION	*Infections which are chronic stress the renal system and generally reduce the persons ability to resist other sources of infection.Chronic pressure sores may contribute to renal upper tract damage and reduce resistance to further pressure sore onset.

INTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

	FACTOR/CATEGORY	SIGNIFICANCE
PSYCHOLOGICAL	COGNITIVE	*Those patients with cognitive disabilities which impede comprehension of pressure sore risk or reduce their ability to comply with protective regimens,are dependent upon others to provide some form of constant support.This often proves to be of limited success.The support surfaces may need to be "foolproof"in such circumstances severely limiting the choice.
	BEHAVIOURAL	*Sitting is a behaviour ,considering posture and movement a voluntary activity,which can be influenced by a patient's attitudes and motivation.A poorly motivated or depressed individual may exhibit decreased activity or attention to selfcare routines,increasing the risk of pressure sores.In some of these circumstances the pressure sore may be a secondary symptom of an unrelated psycho-social upset.Specific sitting habits may be influence by training education and biofeedback techniques.

EXTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

	FACTOR/CATEGORY	SIGNIFICANCE
INTERFACE FORCES	NORMAL	*Forces normal to the support surface produce pressures.The pattern of these pressures or pressure gradients,are responsible for producing ischaemic conditions in the supporting tissues.These patterns are the result of the mechanical properties of the support surface and the anatomy of the weightbearing tissues.Although there is an interdependence between these two factors the mechanical properties of the support surface can be modified to alter these pressure patterns and reduce undesireable pressure gradients.
	IN-PLANE	*The shape and structure of the support surface can influence the combination of in-plane and normal forces exerted on the tissues.With respect to seating surfaces increasing the tilt of the horizontal surface can reduce the tendancy of the patient to slide forward and hence reduce the in-plane forces neccessary to resist movement or sliding.Bennet (1979)has shown that shear stresses induced by these forces decreases the local blood flow to the skin.
	FRICTION	*Dinsdale(1961)demonstrated that the skin abrasion caused by surface friction increased the probability of subsequent ulceration under conditions of prolonged pressure application. The texture of covering materials will determine the coefficient of friction of the support surface and this again is alterable.
ENVIRONMENT	MOISTURE	*The absorbancy of the support surface may alter the moisture or vapour pressure developed at the patient-clothing interface.If the person has moist skin this will increase the risk of tissue maceration.Skin will absorb surface moisture and increase its cooeficient of friction while softening at the same time.
	HEAT	*The thermal preoperties of the support surface will determine the equilibrium temperature at the patient-seat interface.It has been estimated that the metabolic rate increases by 10% for every 1C° increase in cell temperature.In this circumstance where loading conditions decrease or stop blood supply,the warmer tissues would

EXTRINSIC FACTORS CONTRIBUTING TO PRESSURE SORES

	FACTOR/CATEGORY	SIGNIFICANCE
L I F E S T Y L E	ACTIVITIES	*The loading charateristics of a wheelchair user will be strongly influenced by the activities engaged in.School age children will suddenly find that they are in an environment in which they are encouraged to sit still for prolonged periods of time.This reduces the oportunity to obtain pressure relief.If they are involved in wheelchair sports then there will be periods of time when they may have violent movements in the wheelchair with accompanying high loading rates or impacts and shocks.The able-bodied person wears different footwear for changing activities but it is not commonly recognized that the same consideration may be true for wheelchair support surfaces.For this reason it is essential to know the range of activities and their influence on the seating risks.
	REGIMEN	*The effect of pressures produced by prolonged wheelchair sitting will be greatly dependent upon the frequency with which the user gets out of the sitting position completely to provide a long period of pressure relief.This is a form of sitting behaviour which is dependent upon many of the intrinsic risk factors dealing with the patient's attitude,vigilance and planning with respect to self care.By the same token the person at risk may employ other self care techniques such as regularly applying external creams and rubbing skir at risk.Detection of early inflammation and applying protective measures such as short term bedrest can limit accumulative trauma.

STUDY POPULATION

Initials	Age-Sex	Tissue Site Quality	Referral Reason	Seating System - Sitting Time (HR)
J.A.	9-M	ITR-2/1	Research Subject	slung foam (2-5)
O.A.	12-F	S-3/4 S-3/1	Status check Status check	(baseline) (baseline)
G.B.	10-M	S-3/4 S-3/4	Sitting toler-ance trials Sitting toler-ance trials	Roho (baseline) Roho (baseline)
M.C.	17-F	ITL-4/1 ITL-4/2	Sitting toler-ance trials Sitting toler-ance trials	Roho (baseline) Roho (2-0)
D.C.	17-M	ITR-5/2	Status check of surgical flap site	no cushion inter-mittent sitting
C.D.-1	19-M	ITR-4/1 ITR-4/1	Sitting toler-ance, post OP Sitting toler-ance, post OP	Roho (7.0) Roho (9.0)
C.D.-2	29-F	ITL-3/1 ITL-3/2 ITL-3/2	Sitting toler-ance, post OP Sitting toler-ance, post OP Sitting toler-ance, post OP	Roho (baseline) Roho (6.5) Roho (4.0)
C.D.-3	16-M	ITL-2/3 ITL-2/3	Status check Status check	Roho (3.0) Roho (3.0)
C.D.-4	34-F	ITR-4/3	Review	Roho (1.5)
K.D.	28-F	ITL-3/1	Screening	Foam (baseline)
P.F.	20-M	ITR-3/1	Review	Roho (7.0)
D.F.	14-F	ITL-3/1 ITL-3/2 ITL-3/2	Review Sitting Toler-ance Sitting toler-ance	Roho (baseline) Roho (0.5) Standard care (8.0)

Initials	Age-Sex	Tissue Site Quality	Referral Person	Seating System - Sitting Time (HR)
R.G.	23-M	ITR-4/1	Screening	Roho (10)
H.H.	62-M	ITL-4/3	Screening	Bye-Bye(baseline)
J.K.	14-F	ITR-3/2	Sitting tolerance	Standard care (3.0)
		ITR-3/2	Status check	Standard care (baseline)
		ITR-5/3	Sitting tolerance	Roho (1.0)
		ITR-5/3	Status check	Roho (baseline)
		ITR-5/3	Status check	Roho (baseline)
W.K.	60-M	ITL-4/3	Screening	bye-bye(baseline)
F.M.	15-M	ITL-3/4	Status check	(baseline)
		ITL-3/4	Status check	(baseline)
		ITL-3/3	Status check	(baseline)
		ITL-3/2	Sitting tolerance	Contour (2.0)
		ITL-3/2	Sitting tolerance	Roho (3.0)
		ITL-3/2	Sitting tolerance	Roho (2.0)
		ITL-3/2	Sitting tolerance	Roho (baseline)
		ITL-3/1	Sitting tolerance	Roho (2.5)
		ITL-3/2	Sitting tolerance	Roho (2.5)
S.Q.	23-M	S-3/4	Screening	Foam (2.5)
		S-3/2	Sitting tolerance	Roho (4.0)
A.R.	14-F	ITL-4/1	Review check-up	Standard care (3.0)
R.R.	14-M	ITR-2/2	Research subject 23 examinations within a 2 week period	Roho (6.0,2.0,5.5, 2.0, 6.0, 5.5, 3.0, 2.5) baseline x 8. foam (5.5, 3.5) gel (5.0,6.5,2.0)
C.S.	14-M	GTR-1/1	Screening	Contour (4.0)
E.S.	23-M	ITL-3/3	Screening	Foam (baseline)
		ITL-3/3	Sitting tolerance	Foam (5.0)

Initials	Age-Sex	Tissue Site Quality	Referral Person	Seating System - Sitting Time (HR)
T.S.	24-M	ITL-2/1	Screening	Roho (baseline)
S.S.	12-M	ITL-3/1	Sitting tolerance	Roho (4.0)

CODING FOR EXAMINATIONS IN TABLE-6.1

The referrals in Table 6.1 have been classified as follows:

Screening:

This procedure was provided for new patients (either for a baseline or post-sitting test). The clinical objective of the examinations was risk identification prior to team discussion in the weekly Tissue Trauma Clinic.

Review:

Patients who had already been provided with a seating system by the tissue trauma programme, were reviewed at preset intervals of which the maximum was 12 months. The examination focussed on sites known to be at risk.

Sitting Tolerence Trials:

Those patients for whom the best seating system had not been determined, were asked to participate in a series of sitting trials. In addition those patients recovering from skin surgery were monitored daily, as they increased the duration of their sitting time.

Status Check:

Patients were encouraged to contact the team coordinator for energy review if acute changes in tissue condition were observed. These individuals were well known to the programme, and comparative thermographs and photographs were available to assist in detecting acute deterioration or improvement in tissue condition.

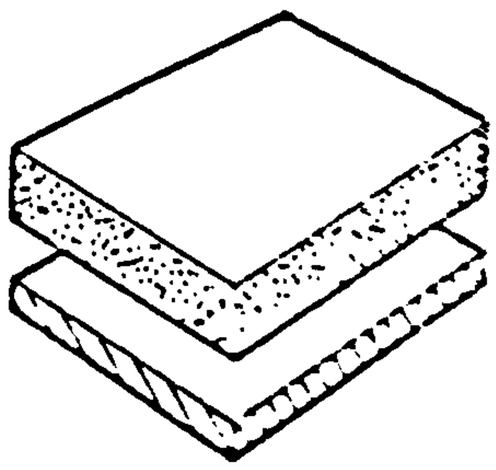
Research Subject:

One subject was admitted for two weeks to participate in the detailed research trials. Baseline and post-sitting examinations were conducted on a variety of seats in conjunction with thermistor and weight shifting studies, not included in this dissertation.

APPENDIX II SEATING SYSTEMS

This Appendix contains examples of seating systems commonly used in the seating programme at OCCC. Many of these have been developed in collaboration between the author and the seating team. Both the physical properties and applications are listed with schematic diagrammes of the systems.

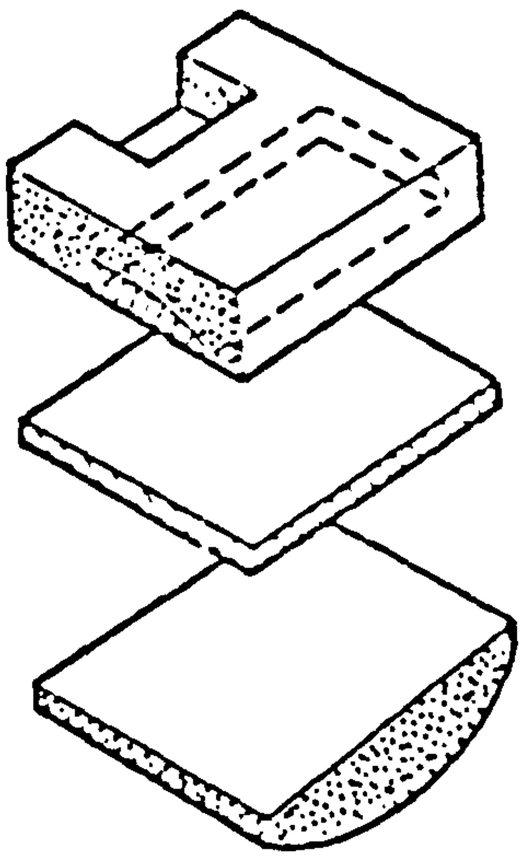
FOAM PLUS BASE



Properties: Foam cushions may contain elastic and/or viscoelastic foams with subsequent mechanical characteristics dependent upon the materials alone. These cushions insulated and develop high interface temperatures rapidly. The cover membrane may also play an important role in effecting the mechanical characteristics if it is rigid, Chow (1975).

Applications: These cushions are the simplest users who are not at an extreme physical risk or are light may do well. These may also serve as inexpensive back up cushions for more elaborate devices which are prone to failure through leakage, Hahn (1977).

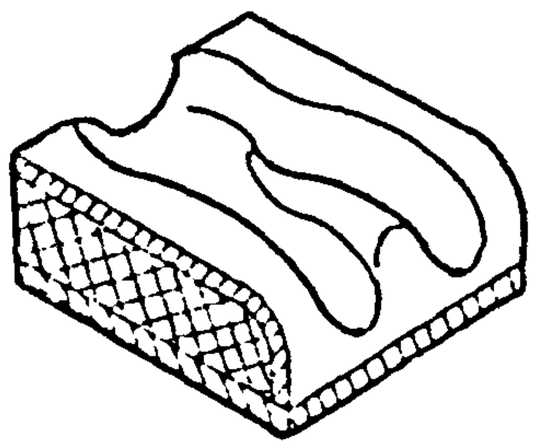
SOFT CONTOURED FOAM



Properties: Contoured soft foam cushions require a solid base to stabilize their shape. This base may be either plywood or shaped rigid foam, Rogers (1974), Mamley (1977), Motlock (1977). The mechanical characteristics with respect to pressure redistribution will be determined by both the design and foam characteristics.

Applications: This type of cushion will accomodate people without major spinal deformities and who are responsible enough to sit in the shape as instructed. Those who have a history of ischial sores may particularly benefit from pressure redistribution to the trochanters and thigh regions. Pressure gauges should be used to check the fit of these systems.

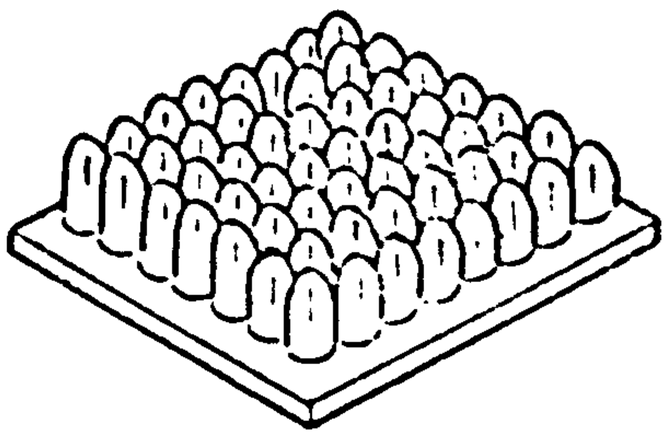
RIGID CONTOURED FOAM



Properties: These cushions have an elastic or viscoelastic foam liner with a molded plastic or foam-in-place shell. They also require a rigid support medium to maintain their shape and use a special wheelchair interface frame for attachment to the mobility base. Hobson (1978), McCluer (1966), and Ring (1978).

Application: Those users who have specific find this comfortable and stable. Often training is required as inaccurate sitting (misalignment) may generate dangerous pressure gradients.

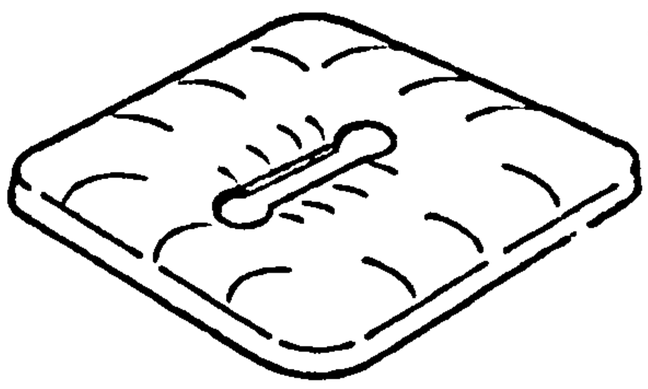
AIR FLOTATION



Properties: Usually these cushions have a rubber membrane with variations of single or multiple cells. The mechanism of support is usually through surface tension in the membrane as supported by the internal gas pressure. The support is characteristically elastic with varying degrees of resistance to inplane forces and friction dependent upon the membrane design and thickness, Graebe (78).

Application: This type of support provides good pressure distribution but may require additional spinal support for users with high lesions. Responsibility is required on the part of the user to protect against punctures and to detect slow leaks.

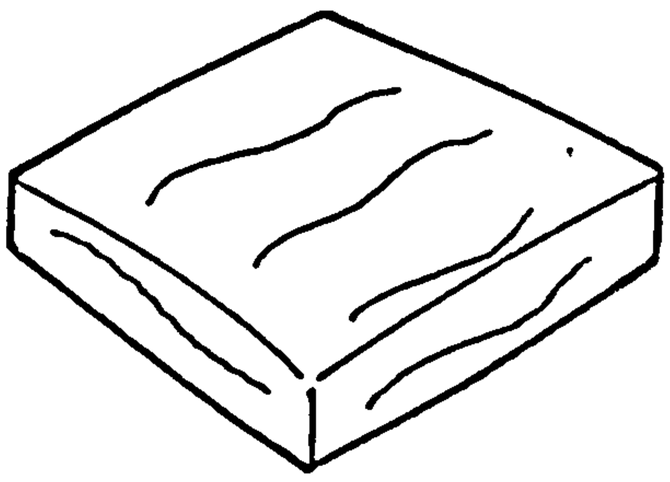
FLUID FLOTATION



Properties: These systems are water or water and foam filled and enclosed in a heavy membrane which limits the displacement of the liquid. The deformation characteristics will depend on the volume enclosed by the membrane and the interaction of internal flow through any enclosed materials. A loose membrane is possible if the internal structure limits the displacement of fluid by its intrinsic elasticity and density. Water is an excellent conductor of heat and there will be a short term cooling effect until an equilibrium is reached, Stewart (1980).

Applications: These cushions do not produce particularly low pressures but are useful where sweating and intolerance to heat is a major concern. Good upper extremity strength is required to independently handle the cushion. They may be unstable for sitting posture producing a slight rolling motion, when the user leans. Responsibility must be used in caring for the device to prevent punctures and sudden failure.

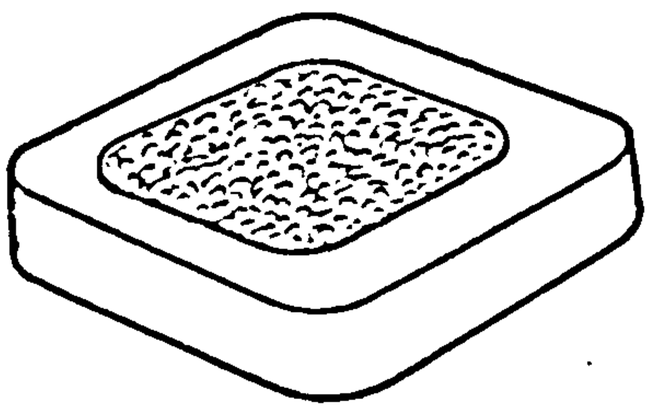
GEL FLOTATION



Properties: The goal of many gel cushion designs is to produce a support surface with a mechanical compliance similar to that of human flesh and thereby reduce pressure gradients under bony prominences. This function will be influences by the rigidity of the membrane and the magnitude of internal forces within the gel resisting displacement. These tend to be heavy and provide some cooling although not to the same extent as the water cushions, Spence (1967).

Application: This type of system reduces interface temperatures during sitting where maceration is a threat due to excessive sweating. It is heavy for independent users to transfer but its instability in the horizontal plane is less severe than the pure water cushions. Caution is required to prevent puctures so that some responsibility is necessary on the part of the user.

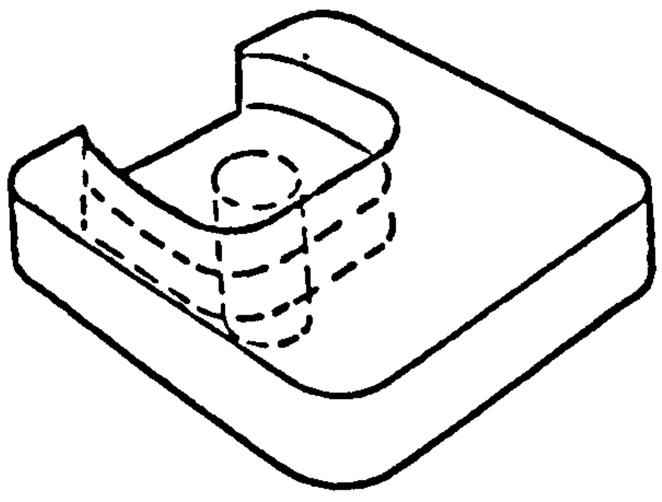
PARTICLE SUPPORT SYSTEMS (BEAN BAG)



Properties: These may be rigid or semi-rigid containers with particles contained in a fixed volume. The support mechanism is based on the transmission of pressure to the container walls and subsequent mechanical interlocking of particles, Jones (78), Lyddy (78). Lubricants can be used to reduce this mechanical interlocking and vacuum dilatency to increase it. Expanded polystyrene beads are commonly used as the particles.

Applications: The self molding properties over all or some of the support surface, depending on the design, provide good pressure distribution around sharply protruding bony prominences. Maintenance is required and with periodic replacement of beads, due to deterioration or leakage if the membrane is damaged, Jones (1978-1979), Lyddy (1978).

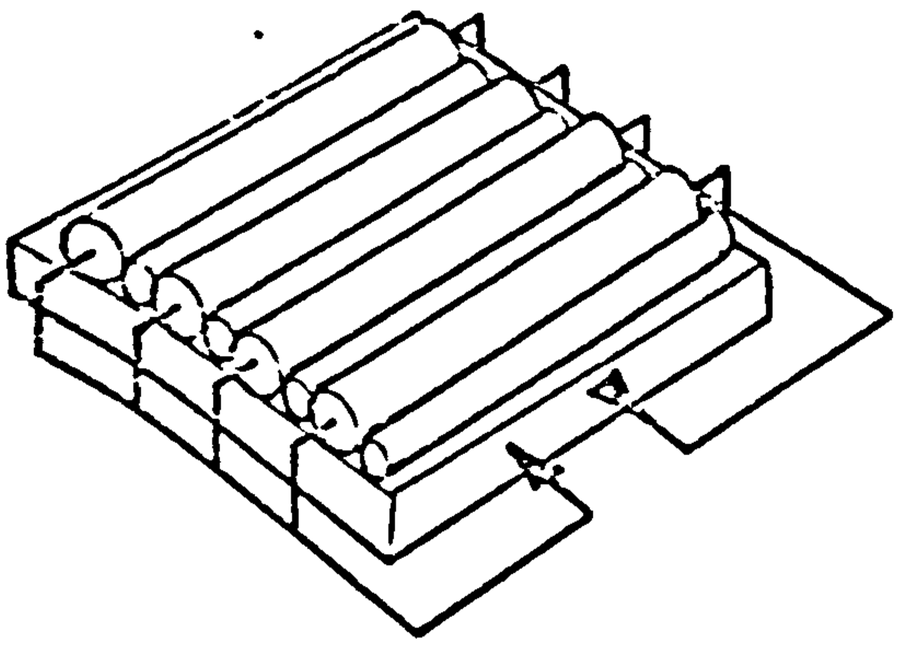
ALTERNATING PRESSURE BY ELEVATION



Properties: The reciprocating seats operated on the basis of regular pressure relief. They usually have a firm surface which moves vertically to load and unload bony prominences. The mechanism may be either powered by battery and gear motor or by chair powered hydraulics, Keane (78).

Application: The best lifting effect would be obtained for users with only mild spinal deformities maintenance users is required with possibility of disastrous failure if there is a power loss. This provides regular pressure relief for users unable to achieve independent good pressure shifting through independent trunk movements or by lifting.

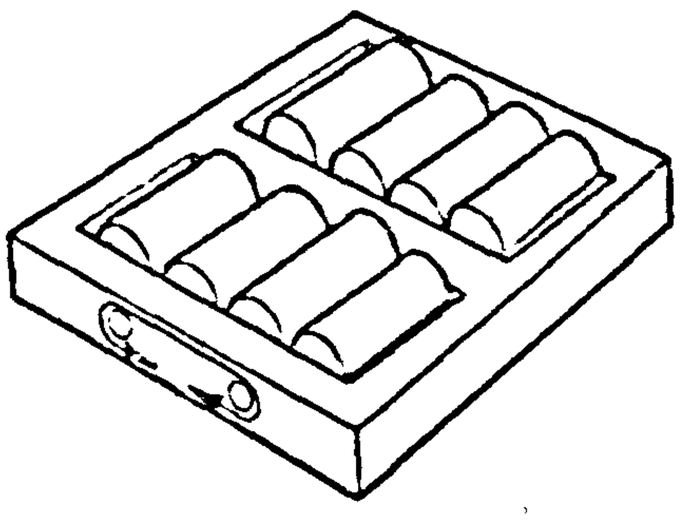
ALTERNATING PRESSURE BY PNEUMATIC CELLS



Properties: Non-stretch membranes must be used to provide pressure changes during alternate inflation-deflation cycles of the bladders. This usually requires a battery powered pump to operate, Stapleton (1979). The mechanics of support may generate internal tissue pressures if the tissue hammocks between inflated cells.

Application: This type of system is commonly used as a hospital mattress and is intended for people unable to shift their own weight. It would be contra-indicated for users with a severe pelvic obliquity.

ALTERNATING PRESSURE BY ROLLERS

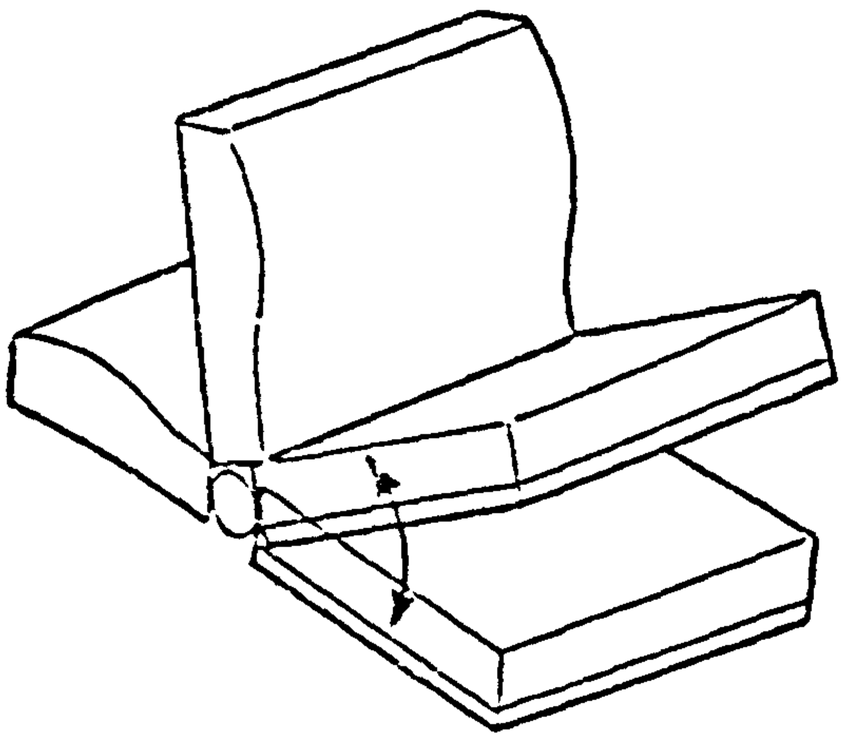


Properties: A rolling contact mechanism can be used to provide large pressure changes in a self-contained battery powered unit, Kosiak M (personnal communication).

Steel rollers are used to maintain low interface temperatures and to provide large pressure changes. New models have shaped rollers and may include a contoured firm foam border to provide a static support where it is tolerable.

Applications: This unit is best adapted for subjects unable to independently alter weight-bearing over their ischial tuberosities. Ther is a risk of transmission of shock loading to subjects with very thin subcutaneous tissues. The user must be responsible enough to detect a power failure and have some contingency plan in the event of a breakdown.

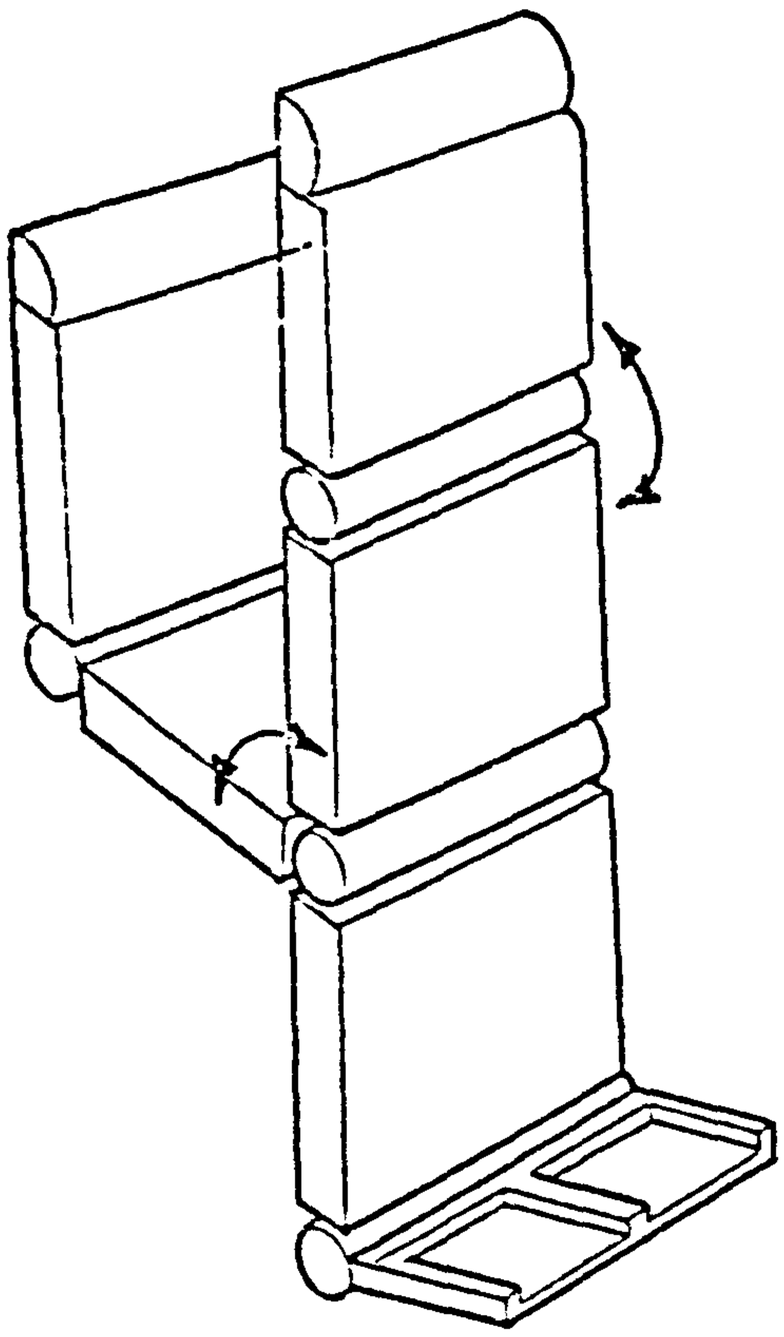
TILT SEATS



Properties: This category of seating systems refers to the support frame not the cushion. Powered or manual devices may include either back tilt, back and base tilt or complete incline at a fixed angle.

Application: The choice of systems depends upon the desired function. Pressure relief may be obtained when the back is beyond 45°. A back tilt alone increases surface shear stress in the weight bearing tissues. Tilting structures also increase the bulk and complexities of the wheelchair support systems and are not readily available. Custom units may well compromise the portability of the mobility base.

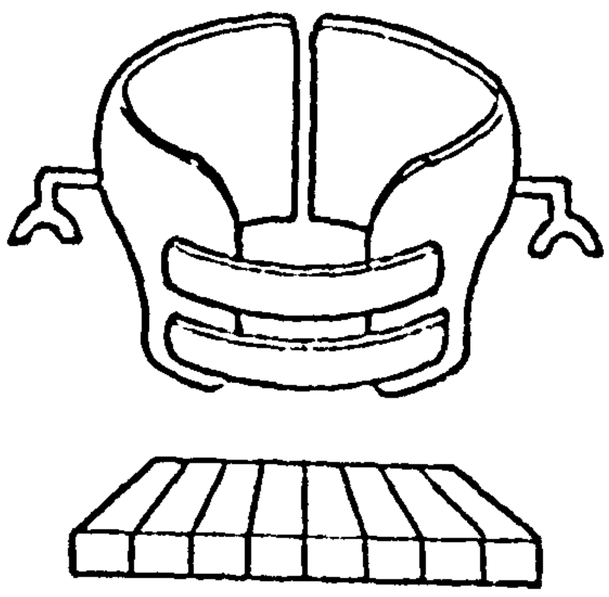
ARTICULATED SEATING SYSTEMS



Properties: Special powered or passive support surface frames to permit standing and weight-bearing through lower extremities have been developed. Most are battery powered, bulky and expensive.

Applications: Users without severe lower extremity deformities and contractures can increase their environmental access. Pressure relief is a secondary benefit and would not be the primary reason for prescribing such a system.

THORACIC SUSPENSION



Properties: These molded shells are either vacuum formed or laminated with fixtures for wheelchair suspension. Hinged back and an interlocking anterior clasps are required along with proper orthotic fitting techniques. Black (75)

Applications: The thoracic suspension may be used to provide complete or partial weight relief from the pelvis during sitting. Subjects having a narrower waist than chest and low body weight (best with young children although the resultant immobility may be a contraindication) have tolerated this type of system for up to 12 hours use. This device is a last resort but permits continued sitting during skin healing.

APPENDIX III FORMS

Typical data collection forms are shown in this Appendix to demonstrate the format used in formalizing the assessment process. The data sheets were designed by the author with the intent that they would prompt the examiner to use a standard approach in entering objective information.

a) clinical examination sheet and summary code sheet

b) thermistor and movement monitor data sheet

c) combined fitting , pressure and glass table examinations

d) microfishe data retrieval forms

TEXT BOUND INTO

THE SPINE

SE TRAUMA DATA DATE: NAME: CHART #:

DIAGNOSIS: AGE: SEX:

EL OF LESION

	Motor L	Motor R	Sensory L	Sensory R
oracic				
per Lumbar (T12-L2)				
ver Lumbar (L3-L4)				
abo-Sacral (L5-S2)				
t-Fem Sparing				

MEDICAL PARAMETERS

Weight	L	M	H
Nutrition	G	F	P
Anemia	M	M	S
Renal Function	G	F	P

THOPEDIC DEFORMITIES

cle Tone	Hypo		N		Hyper	
liosis	NA	M	M	S		
hosis	NA	M	M	S		
. Instrumentation	Y		N			
t. Instrumentation	Y		N			
vic Obliquity	NA	M	M	S		
Flexion Contr.	L		R			
uction Contr.	L		R			
uction Contr.	L		R			
Rot. Def.	L		R			
locations	L		R			
e Ext. Lag	10	30	90	10	30	90
e Flexion Lag	10	30	90	10	30	90

SKIN HISTORY

	None	Seldom	Frequent	Skin Grafts	Rotation Flaps	G) Subcutaneous Tissues P)	Deep Induration
Sacro-Coccygeal							
Ischial (R)							
Ischial (L)							
Trochanter (R)							
Trochanter (L)							
Spine (Lumbar)							
Spine (Thoracic)							
Feet							
Other:							

LOGY

	G	F	P
eral Hygiene			
el Continence			
dder Continence			
pers			
heter (Intermit)			
ernal Collecting			
heter (Indwelling)			
oconduit			
ificial Sphincter			

ORTHOTICS

None			
AO			
BKO			
AKO			
U.Ext.Aids			
Parapodium			
W. Chair	½	½	1
Fit to W.C.	G	F	P
Wooden Base			
Foam			
T-Foam			
Gel			
Rocker			
Beanbag			
RDHO			
Susp. Sleeve			
Reclining WC			

PSYCHOLOGY

	G	F	P
Self Image			
Knowledge			
Motivation			
Attention Span			
Education Level			
Vocat. Status			
Independence			
Social Activity Level			

Trunk Position
Cushion
Leg Position
Foot Plate Contact
Scoliosis
Instrumentation
Pelvic Obliquity

8. Kyphosis
9. Pelvic Tilt
10. Sp. Rotation (pelvis w.r.t. shoulders)
11. Joint Range
12. of movement
13. Hips - Intact
- Dislocated
- Subluxed

14. Skin Map (Scar.)

Pressure Sites
15. Coccyx
16. L. Trochanter
17. L. Ischium
18. R. Trochanter
19. R. Ischium

KEY

G F P
Good Fair Poor

M M S
Mild Mod. Severe

L R
Left Right

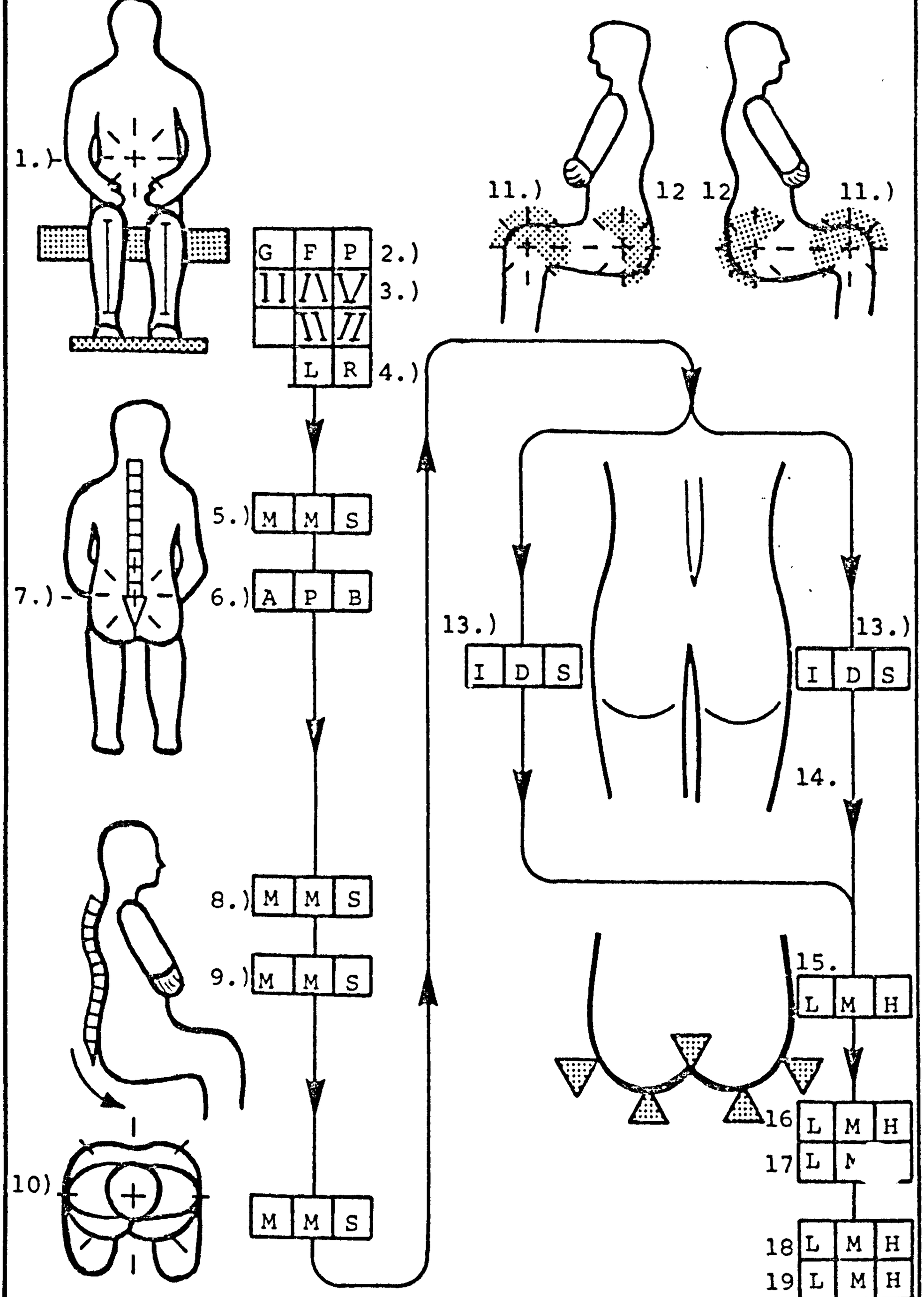
L M H
Light Mod. Heavy

Y N
Yes No

A P B
Ant. Post. Both

NA
Not Applicable

½ ½ 1
Fraction of Day in Chair



REHABILITATATION ENGINEERING DATE _____

THERMAL SEATING ASSESSMENT DATA SHEET

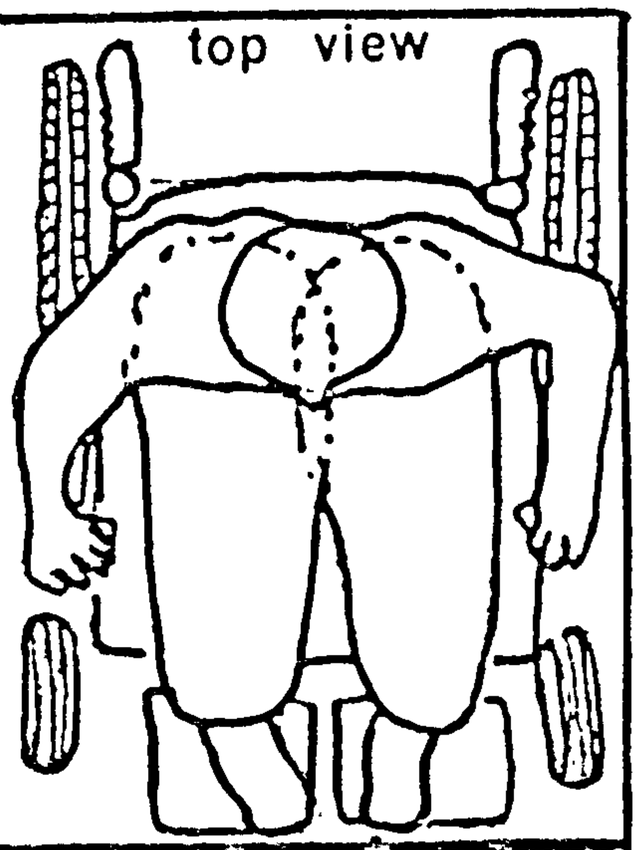
NT _____

T NO _____

☐ FILE NO ☐

seating system

top view



MOVEMENT DATA FORM

apsed (sec) ·T	Left	Right			SITE NO	1	2	3	4	5	6
ff (sec) A			(L/R)	INTERFACE	skin						
down (sec)T-A			(L/R)		cushion						
lifts B			(L/R)		base						
ratios. T-A/A			(L/R)								
ates B/T			(L/R)								

RPRETATION _____

_____

INVESTIGATOR

L FILE [ ] REHABILITATI - 288 - SSUE TRAUMA) INITIATION: / /
COMPLETION: / /

T: THERAPIST: CHNICIAN:

NO. - - PRESCRIP. NO. JOB NO.

patient)

IMENSIONS

cutouts)

ASE SIZE

TY BASE
SIZE manual___ powered___ casterC.___ Str.B___
N.Adult___ Jr.13___ Gr.13___ Tiny Tot___ Mon.B___

CODES FOR PROGRAMME ANALYSIS
DIAGNOSTIC ____
SEATING ____

SUPPORT SYSTEM DIAGRAM

OSIS: AGE:

PROBLEM LIST

fittting supervisor

SYSTEM COMPONENTS AND MATERIALS

COVERS:
terry cloth___ tricot ___
naugahide ___ horsehide___

BASES: horizontal vertical
hammocked ___ ___
plain ___ ___
suspended ___ ___

FOAMS: (in) (in)
polyurethane___ T-36 ___
ethafoam ___ T-41 ___
plastazoate___ T-51 ___

STRUCTURE (trunk support):
POSITION LT--RT--POST
none ___ ___ ___
SHAPE
flat ___ ___ ___
simple curve ___ ___ ___
complex curve___ ___ ___

SUPPORT SURFACE CLASSIFICATION:

foam,plain ___
foam,contoured,soft ___
foam,contoured,hard ___
molded,soft ___
molded,hard ___
flotation,air ___
flotation,water ___
flotation,gel ___
flotation,particle ___
reciprocating ___
alternating ___
tilting ___
stand-up ___

DEVICES:
warning system ___
flip wheel ___

TESTS:
pressure ___
interface temperature ___
thermography,baseline ___
thermography,stress ___
home trial ___

COMMENTS:

CENTRAL FILE ☐

REHABILITATION ENGINEERING

DATE: ___/___/___

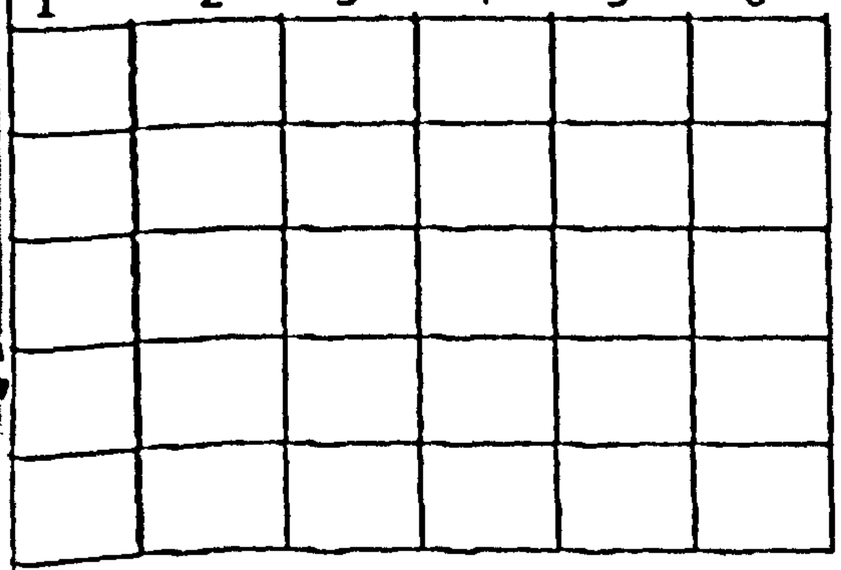
BIOMECHANICAL SEATING ASSESSMENT DATA SHEET

computer storage:TD__ __ FILE__ __

PATIENT: THERAPIST: REHAB:

LOCATIONS OF TRANSDUCERS

1 2 3 4 5 6



POSITIONS:

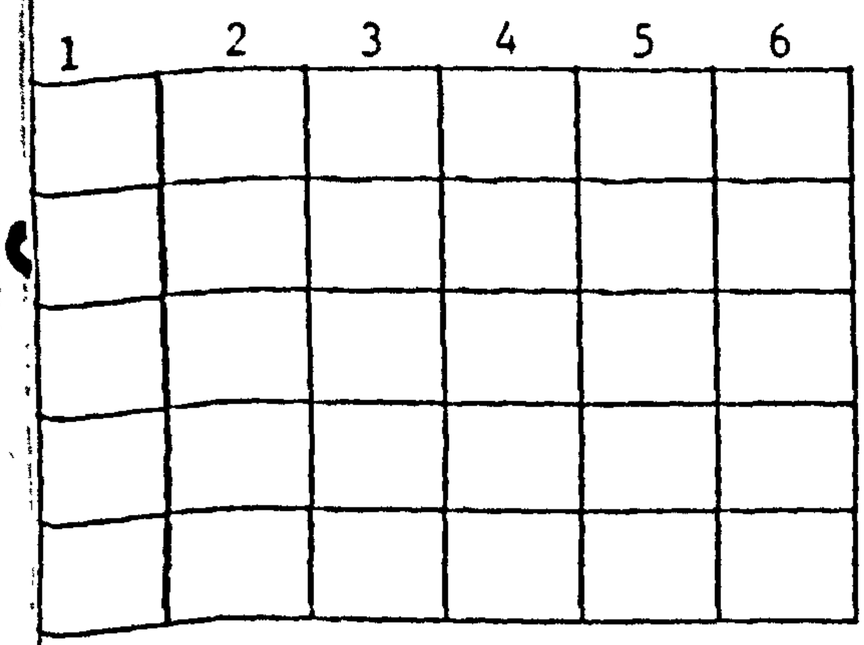
vertical

left

right

forward

other



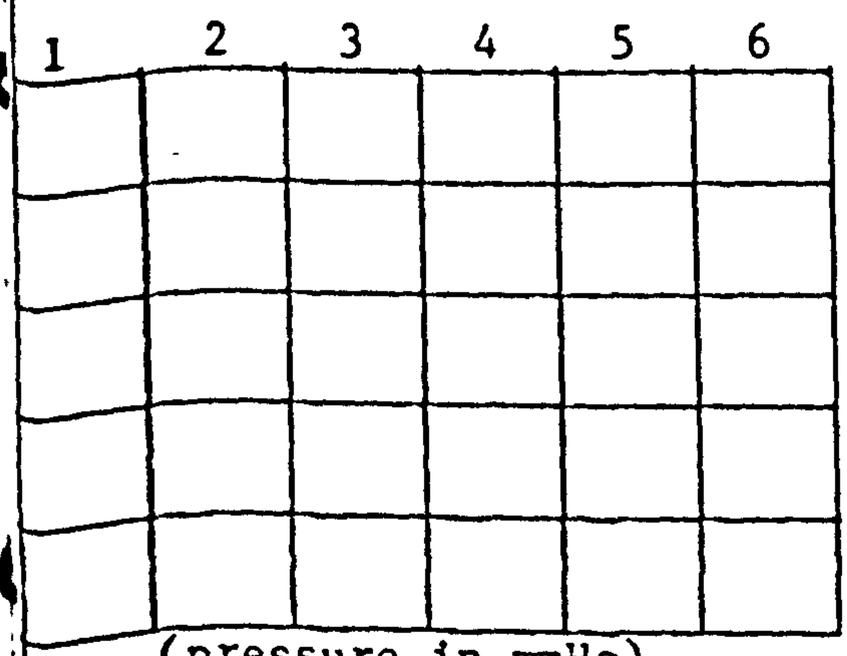
vertical

left

right

forward

other



vertical

left

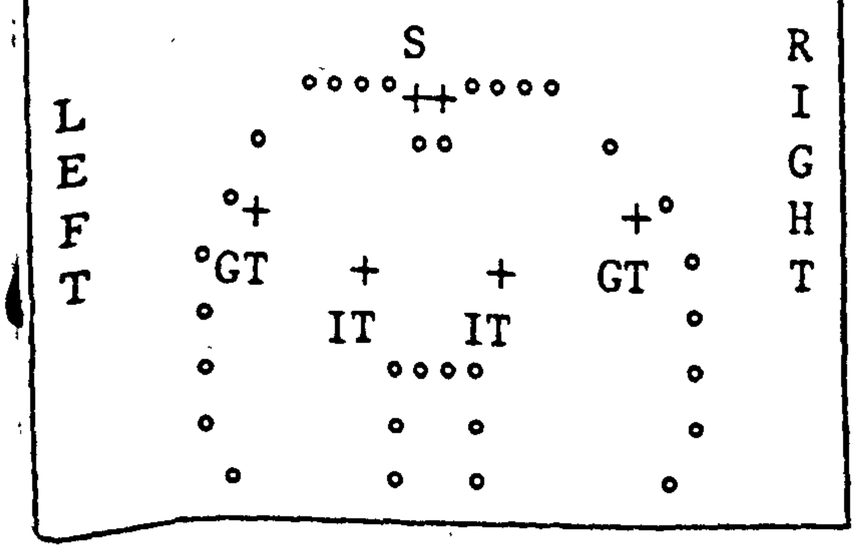
right

forward

other

(pressure in mmHg)

GLASS TABLE ASSESSMENT



SEATING SYSTEMS & COMMENTS

RISK COMMENTS:

SEATING RECOMMENDATIONS:

APPENDIX IV SOFTWARE PROGRAMMES

Introduction

Two sets of software programmes were developed during the course of this research. The tests reported in Chapter 5, conducted at DCIEM, made use of a Hewlett Packard data acquisition and processing system. The software was developed through Mr. R. Limmer of DCIEM and Mr. A.F. Filippone of OCCC. Following this phase of the project, a second set of more extensive analysis programmes were developed by Mr. Filippone based on the Tektronix 4051 and 4052 systems. These were developed in BASIC and a software book of programme listings has been compiled (available from the author or the Rehabilitation Engineering Department of OCCC). Mr. Tissa Jayasinghe developed the statistical programmes to analyse the peak temperature results reported in Chapter 4 and the population risk analysis in Chapter 7. The author's contributions in this aspect of the research were in the areas of defining approaches, objectives and interpretation of results.

This appendix lists the software programmes developed with brief descriptions and flowcharts where required. This appendix is jointly authored with Mr. Filippone.

A number of computer programs have been written in the BASIC language to assist in the acquisition, storage, processing and display of areameter thermographic data. Although many versions of these programs have been generated in the development, only the most up-to-date ones are listed and a short description of the function of each is given.

The first step in the processing of the experimental data has been to calculate average (T_{avg}) and maximum (T_{max}) temperatures of

the "windowed" area. Since the areameter had been designed to sample only 10 isotherms, care has had to be exercised in the choice of sensitivity (S) and calibration temperatures (T_{cal}) used, so as to maintain the total area of interest within the temperature range throughout the observation part of the experiment. This has allowed for valid T_{avg} calculations using the equation for the weighted mean:

$$T_{avg} = \frac{\sum A_i}{\sum_1 A}$$

where: $i = 1^{th}$ temperature channel

A_1 = area in i^{th} channel

T_1 = temperature of i^{th} channel

At this point, a history of average temperatures of one minute intervals through the examination period exists. Comparison of such variations in thermal history from subject to subject and examination to examination has provided for one method of detecting variations between subject's thermal skin responses arising from seating circumstances and skin condition.

A good method for maintaining the level of information gathered yet providing as much data compression as possible has been found necessary.

By the use of polynomial curve fitting, it has been possible to generate a compact matrix of objective descriptors for comparative and classification purposes.

These descriptors are actually the "K" coefficients of the mathematical quadratic curve fit to the natural log of the average temperature points (Tektronics Plot 50 mathematics Vol. 2).

Plotting of these coefficients against each other in a "descriptor"s15 provided an opportunity to compare dynamic changes in skin temperature quantitatively.

The following programs and their description enlarge on the above outline.

PROGRAMME LIST

		Computer File
1.	Thermistor Data Acquisition and Retrieval	F2, F3
2.	Areameter Data Acquisition and Retrieval	F4, F5
3.	Average Temperature Calculation (1)	F7
4.	Average and Maximum Temperature Calculations	
5.	Semi-log Curve Fitting Programmes	F8, F9, F10
6.	Optimum Polynomial Curve Fitting	F11
7.	Cubic Spline Fit	F12
8.	DCIEM Areameter Data Storage	F13
9.	DCIEM Data T(Calibration) and Sensitivity Insertion	F14
10.	DCIEM Average Temperature Calculations	F15
11.	K-Matrix Plotting	F16,F17,F18
12.	Modelled Average Temperature Display	F19
13.	Peak Temperature, Data Entry	F20
14.	Peak Temperature, Calculation of Means and Standard Deviations	
15.	Peak Temperatures, Pearson Correlation Coefficents	

1A Thermister Data Acquisition

This programme was designed to sample up to ten thermistors at programmable intervals. The timing signals were software controlled originating

from the Tektronix 4051/4052 computer and operating through the multiplexor to read the thermistors voltages. The thermistors were connected to a voltage divider circuit which produced potential differences proportional to the thermistor temperature.

The CNVRT subroutine utilizes an equation generated by curve fitting temperature vs. thermistor resistance coordinates as determined by the manufacturer. This equation is valid only for the temperature range of 15-40°C. This programme also incorporates some degree of compensation for errors introduced by the hardware. Although all thermisters can be used to monitor any temperature desired, two were reserved for measurement of "dry" bulb and "wet" bulb temperatures in ambient air stream. A reference look up table was included in the software to yield relative humidity values from the differential or the dry and wt bulb reading. A small fan was mounted in an air duct to produce a constant airflow for these readings. All thermisters sampled ten times per reading and the average calculated to minimize errors. This processed data was then stored on magnetic tape and displayed on the CRT screen as plots of temperature vs. time amid % relative humidity .

1B Thermistor Data Retrieval

The basic thermistor data was retrieved by the previous programme. These values once retrieved were displayed in the form of a composite graph incorporating "6 site" temperature readings plus separate plots of (Tamb) and R.H. versus examination time. Expanded individual graphs could be optionally displayed and maximum, minimum and average temperature values superimposed by horizontal lines.

Any number of such expanded "site" graphs could be superimposed to provide direct comparison of temperature history curves from site to site.

2.A Areameter Acquisition

This is the main acquisition program for thermographic data. It incorporates the thermistor acquisition programmes which sample both dry and wet bulb thermistors to calculate and plot the ambient temperature and percent relative humidity. The ambient conditions were monitored throughout the examination procedure. Any coicident perturbations in these values and the data could be identified to established the presence of any transient artifacts.

The main purposes of programe are to:

1) provide timing for areameter data sampling through the examination period.

2) read the analog signals from the areameter and convert these to meaningful, digital data suitable for storage and display

3) provide autdio-visual cues for the operator prior to data sampling so as to have the subject in an optimum position and to synchronize the taking of plots graphic records with the established protocol.

4) prompt the operator to enter subject/examination identifiers and calibration and sensitivity data for later reference and data retrieval.

5) store data

2.B Areameter Data Retrieval

The basic purpose of the program is to retrieve data stored by the previous programme, 2B, from magnetic tape files. In addition

approximately scaled axes on the CRT screen or plotter are generated including: subject identification, examination identification, summed area axes, ambient temperature, % relative humidity. Finally it will plot data curves in the appropriate axes.

3. Temperatures

Although this program is relatively complete and is found in its own program file F6, it was originally intended as a subroutine within programme #2, areameter acquisition. It has been modified to (1) retrieve theraw area data recorded by the areameter acquisition program (F4) along with calibration and temperature scaling information, (2) convert these values to average temperatures of the subject area enclosed by the areameter window, and (3) display this average temperature along with environmental temperature and relative humidity either on CRT, hard copy or plotter.

The calculation of average temperature from the areameter window data was found using a weighted mean formula:

$$T = \frac{\sum_{i=1}^{10} a_i T_i}{\sum_{i=1}^{10} a_i}$$

where T = weighted average temperature

T_i = temperature of i^{th} areameter channel

a_i = area at i^{tn} channel encompased by window

i = channel number of areameter reading

4. OCCC Area Data to Temperature

This programme was similar to the average temperature calculation (F6), however, it is more streamlined and modular. In addition to these calculations and plots it also records these areameter window temperatures in a separate magnetic tape file for further retrieval or processing. The curve of maximum temperatures present within data window throughout the examination can also be plotted.

5. Semi-log Curve Fit Programs (F8, F9, F10)

This program generates plots of the following curve fits: i) linear (Thermog/F8), ii) exponential (Thermog/F9), iii) power (Thermog/F10). All three programmes have been adapted from the Tektronix 4050 Series GPIB Support Software Manual. This has been used to generate a mathematical curve to fit the actual average temperature points of each thermographic examination as calculated by the average temperature calculations in (F7). These mathematically generated curves and actual temperature points were superimposed over same axes for visual comperison. This was originally used in order to decide upon the type of data fitting to be used in later programs.

6. Optimum Polynomial Curve Fit (Thermog/F11)

This program was adapted from the Tektronix Plot 50 Mathematics Volume 2. It provided a lease square fit of imput data to a polynomial of degree n. This was adated for: n = 2 (ie. a parabola) for the average temperature. The parabolic fitting, however, was done on the natural log of the average temperature. That is:

$$\ln(t) = a + bt + ct^2$$

where T = the weighted average temperature

t = time

a,b,c = coefficients

Once the curve fitting had been performed the values of a,b, and c were known for each set of average temperatures thus rewriting the above equation for ln (t) yields:

$$T = K_0 e^{k_1 t + k_2 t^2}$$

where $k_0 = e^a$
$k_1 = b$
$k_2 = c$

In addition the program also generated the r^2 value or "goodness of fit".

where $r^2 = 0$ implies random distribution of points

$r^2 = 1$ implies that all points lie on mathematically defined curve.

The output of this program was an array giving:

r_1^2 , k_{0i}, k_{1i}, k_{2i}

for all examinations (i=1 to n)

K_0, k_1 and k_2 provided a normalized description of how the average temperature varied through the examination time and the r^2 indicated how good an approximation this was. These coefficients provided a form of data compression as well as an objective basis of comparison for average temperatures. Selection criteria were used to define populations of data such as common subjects, seats, or sitting times. Although fitting of data points can be more precise using polynomial curves of higher degree, the number of unknowns (k parameters) increases and larger sample populations are required.

7. Cubic Spline Fit

This program normalized the average and maximum temperature values by a cubic spline technique obtained from the Tektronix PLOT 50 mathematics Vol.2 package. Its purpose was to:

a) retrieve areameter data from tape;

b) calculate ambient temperature and relative humidity;

c) calculate average and maximum temperature points;

d) calculate progressive area sums;

e) provide an output of all coefficients necessary to describe the variation with time of any of the above curves; and

f) plot graphs of the above calculated using cubic spline fit formula.

Althougn the cubic spline provided for an excellent fit of all data points the number of descriptive corefficents was 4 x (N-1) for N data points yielding no advantage in data compression or additional opportunity for comparative analyses.

8. DCIEM Areameter Data Storage

This program provided for keyboard entry of the DCIEM areameter data. This was necessary as the Hewlett Packard data format was not compatable with the OCCC system. The program provided for storage of areameter data, calibration and identification into a compatible format for analysis by the OCCC analytic programmes. The average temperature and k-matrix plots were required for comparison with the OCCC data. The program also redisplayed data after entry in order to allow correction of entry errors if necessary.

9. DCIEM Data T(cal) and S

During the experiments at DCIEM recalibrations were frequently used during the collection of data to alter the scanned temperature range. The purpose of the program was to:

a) retrieve data stored using Thermog/F(13);

b) recalibrate if necessary so as to be in agreement with DCIEM data calibration temperatures and sensitivity (as confirmed by DCIEM staff); and

c) restore recalibrated areameter data.

Unlike OCCC data storage routine in which calibration temperature and sensitivity remain constant (within experimental error) throughout the examination period and in most cases from examination to examination this program allows for constant updating of these two quantities at each sample reading within any thermographic examination.

10. DCIEM Areadata to Temperature

This program calculated the average temperature values from the DCIEM data. Due to constant calibration and sensitivity updating of area data the temperature rescaling of areameter channels must be performed for each sample point. The average temperatures were calculated as outlined in the previous average temperature program (F6). The average temperature were stored in exactly the same format as that used in Thermog/F7, although no maximum temperatures were generated. This processing of the areameter data left them fully compatible as imputs to the curve fitting programs.

11. k-Matrix Plotting Programs

a) k_0 vs k_1 (Thermog/F16)

b) k_0 vs k_2 (Thermog/F17)

c) k_1 vs k_2 (Thermog/F18)

Scatter diagrams were used in this program to provide preliminary comparative plots of k_0, k_1 and k_2 coefficients.

12. Modelled Average Temperature Calculations

This program displayed plots of the mathematical curves generated by coefficients k_0, k_1 and k_2 superimposed on the same axes with plots of actual average temperature experimental points. These plots were available as CRT display, hard copy or graphic plotter printouts. Any number of examination data sets could be superimposed on the same axes for visual comparative purposes.

13. Peak Temperature Data Entry

This program facilitated the keyboard imput of maximum temperatures, tissue quality parameters, seat types and sitting times as obtained from the microfiche thermographic files. The results of this program are reported in Chapter 4. This data was stored in array format in various magnetic tape data files in preparation for statistical analysis and correlation routines such as: (1) Peak Temperature Program*; (2) Person Correlation Program*.

* - by Tessa Jasjasingbe