UNIVERSITÉ D´ORLÉANS

LABORATOIRE PRISME

Ecole Doctorale MIPTIS

Thèse presentée par

Monsieur **Luis VILCAHUAMAN**

préparée à PRISME-Polytech Orléans et à l'Université PUCP de Lima

soutenue le 3 décembre 2013

pour obtenir le grade de Docteur de l'Université d'Orléans

en Sciences et Technologies Industrielles

Thèse écrite et soutenue en langue anglaise

EARLY DIAGNOSIS OF DIABETIC FOOT USING THERMAL IMAGES

JURY :

Mr Gérard JACQUET	Rapporteur, Professeur à l'Université de St-Etienne
Mr Guy FEUILLARD	Rapporteur, Professeur à l'ENIVL de Blois
Mr Rachid HARBA	Directeur de thèse, Professeur à l'Université d'Orléans
Mr Raphaël CANALS	Co-encadrant, Maître de Conférences à l'Université d'Orléans
Mr Philippe EMY	Médecin hospitalier au CHR d'Orléans
Mme Martha ZAQUERA	Maître de Conférences, Université Javériana de Bogota
Mr Christophe LÉGER	Président, Professeur à l'Université d'Orléans

Contents

List of figures

List of tables

1. Introduction to the thesis

Scientific context

Diabetes is a major public health problem that is increasing dramatically. In 1995, the World Health Organization has estimated the prevalence of diabetes in the world at 4% and the number of diabetics to 135 millions. In 2009, 347 millions were suffering this disease, and 500 millions are expected in 2030 corresponding to a prevalence of 5.4%. In 2004, 3.4 millions died from diabetes. Diabetes is the seventh cause of mortality in the world.

Diabetes related diseases mainly affect the eyes, the kidney and the foot. In this work, we will focus on diabetic foot. Diabetic foot diseases include neuropathy, peripheral arterial diseases (ischemia), and infection. In the presence of a triggering factor, it may lead to ulceration and subsequent amputation. The annual incidence of foot ulceration among people with diabetes is approximately of 2%, and 15% of these will lead to a lower limb amputation. This implies that nowadays 600.000 diabetic foot ulcers occur each year in the EU-27 of which 90.000 will require an amputation.

In many cases, development of diabetic foot disorders can be avoided or substantially delayed with adequate treatments that are provided at an early stage. It points out the importance of an early diagnosis of diabetic foot done by specialized medical doctors in hospitals. In diabetic foot, diabetes treatments are associated with therapeutic footwear, diabetic foot education, and regular foot care. However, the incidence of serious complications, *i.e.* the occurrence of an ulcer, could further be reduced according to diabetes experts. Most of the research concerning diabetic foot follows these two main directions:

- Improve the early diagnosis of diabetic foot in hospitals,
- Reduce ulcers occurrence and related amputation in diabetic foot.

Among all possible features than can help in such tasks, temperature is an important characteristic. In the recent past years, traditional infrared camera has made tremendous progress. Their price has been dramatically reduced while the technical progress strongly increased. Such technologies are serious candidates for detecting thermal changes in diabetic foot disorders. All these reasons make that the interest of measuring the temperature of the foot becomes more and more an active topic as proved in the two following sections.

The plantar foot temperature is close to 32°C. For a control person (no diabetes), the temperature distribution in the plantar foot is not uniform and shows what is called a bilateral butterfly pattern [Chan, 1991]. In addition, plantar foot temperature varies in diabetic foot due to thermoregulations problems related to neuropathy and/or ischemia, and also in case of inflammation. No typical form exists as in normal persons but several shapes can be observed. In both cases (controls and cases), the possible variations of the plantar foot temperature are usually lower than 4°C. In a recent work, [Nagase, 2012] studies the variations of plantar foot temperature linked to ischemia. He concludes that a wider variation is present in diabetic patients than in control subjects. Another way to estimate thermoregulation problems is to perform a cold stress test [Balbino, 2012]. The temperature difference before and after the cold stress is shown to be interesting in the early diagnosis of diabetic neuropathy.

On the other hand, studies demonstrate that there is a relationship between increased temperature and foot complications in diabetes: increased temperature may be present up to a week before a foot ulcer occurs [Armstrong, 2007]. Temperature of corresponding area of the right and left foot do not usually differs more than 1°C in diabetic foot. A temperature difference greater than 2.2°C is considered as abnormal. Detecting this increased temperature between the two feet and providing adequate therapy can reduce the incidence of foot ulcer by 3. This result of major importance made that several research teams, sometimes associated to a private company, have proposed or tested at home devices to monitor foot temperature [Roback, 2010]. These devices should be low cost and easy to use. However, no already proposed system seems to be widely used because they did not fulfilled the previous requirements. None of them was based on thermal camera. One of the conclusions in [Roback, 2010] was to say that traditional infrared cameras are serious candidates for detecting at home, in a near future, these thermal changes in diabetic foot disorders.

Object of the thesis

The general objective of the thesis relies in the domain of diabetic foot and follows the two already mentioned research directions: improve the early diagnosis of diabetic foot and reduce ulcers occurrence in diabetic foot. It will be based on the analysis of IR thermal images of the plantar foot. The possible directions are twofold:

- Find new strategies to improve the early diagnosis of diabetic foot in hospitals from the analysis of thermal images,
- Design and test a at home system to monitor foot temperature using an IR camera.

The second objective will require the development of a dedicated system using an IR camera to measure the temperature of the plantar surface at home. Developing and testing such a device in a very limited time is a difficult issue. It was not chosen here. This work will be mainly devoted to the first objective and the thesis is entitled:

EARLY DIAGNOSIS OF DIABETIC FOOT USING THERMAL IMAGES

The first step of the project will be to perfectly understand the variations of temperature that occur in diabetic foot before an ulcer may appear. Theses variations are multi factorial. They are mainly linked to blood circulation problems, to neuropathic problems, and to infection. It is expected to improve the early diagnosis of diabetic foot in hospitals.

Organization of the thesis report

This thesis report is structured as follows.
In chapter 2, the definition of diabetes and its various forms will be given. Diabetic foot diseases will be presented. The interest of the thermal approach in these cases will be demonstrated.
The following chapter 3 will be devoted to the use of thermal images in various domains, and will particularly focus on the applications in the biomedical domain. Related work for the diabetic foot will be shown and discussed. The last part will be devoted to the choice of the thermal camera for the project.
From previous analysis, chapter 4 will describe the image acquisition protocol, and the image processing methods developed in this work to assess thermal variations of the plantar foot.
Chapter 5 will present a transversal clinical study were several diabetic thermal foot images will be analyzed.
Finally a conclusion will be given and perspectives of this work will be proposed.
Four appendixes are also present: the first one is related to the technology of infrared sensors, the second to the medical agreement related to this work in the hospital Dos de Mayo in Lima, the third one shows the image database of the medical study, and the last one concerns parameters of the database.

General context

Luis Vilcahuaman is a teacher at the Pontificia Universidad Catolica del Peru in Lima. In 2008, he started a PhD thesis at the University of Orléans under the supervision of Professor Rachid Harba, and with the help of Associate Professor Raphaël Canals. The project also involves the hospital Dos de Mayo in Lima and the Orleans hospital. During his PhD, Luis Vilcahuaman receives the support of the two universities as well as the support of the French Embassy in Peru (Raul Porras Barrenechea grant).

Recently the University of Orléans and the Pontificia Universidad Javeriana of Bogota (associate Professor Martha Zaquera) get a financial support through an ECOS-Nord project to continue working on thermal images of diabetic foot. Martha Zaquera is strongly involved in the project. It also concerns the hospital of the Javeriana University.

Introduction (in french language)

Contexte scientifique

Le diabète est un problème majeur de santé publique qui augmente de façon significative. En 1995, l'Organisation Mondiale de la Santé a estimé la prévalence du diabète dans le monde à 4% et le nombre de diabétiques à 135 millions. En 2009, 347 millions souffraient de cette maladie, et 500 millions sont attendus en 2030 correspondant à une prévalence de 5,4%. En 2004, 3,4 millions sont morts du diabète. Le diabète est la septième cause de mortalité dans le monde.

Les maladies liées au diabète touchent principalement les yeux, les reins et le pied. Dans ce travail, nous nous concentrerons sur le pied diabétique. Les maladies associées au du pied diabétique comprennent la neuropathie, les maladies artérielles périphériques (ischémie), et les infections. En présence d'un facteur déclenchant, elles peuvent conduire à des ulcérations allant jusqu'à l'amputation. L'incidence annuelle des ulcères du pied chez les diabétiques est environ 2%, et 15 % d'entre eux mènera à l'amputation partielle ou totale d'un membre inférieur. Cela implique que de nos jours 600.000 ulcères du pied diabétique se produisent chaque année dans l'UE-27, dont 90.000 nécessiteront une amputation.

Dans de nombreux cas, le développement des troubles du pied diabétique peut être évité ou fortement retardé avec des traitements appropriés qui sont prodigués à un stade précoce. Ceci montre l'importance d'un diagnostic précoce de pied diabétique fait par des médecins spécialisés dans les hôpitaux. Pour le pied diabétique, les traitements du diabète sont associés à l'utilisation de chaussures thérapeutiques, à l'éducation de malade concernant le pied diabétique, et à des soins réguliers des pieds. Toutefois, l'incidence des complications graves, c'est à dire l'apparition d'un ulcère, pourrait encore être réduit selon les experts du diabète. La plupart des recherches concernant le pied diabétique suivent ces deux directions principales :

• Améliorer le diagnostic précoce du pied diabétique dans les hôpitaux,
• Réduire les ulcères et les posibles amputations liées au pied diabétique.

Parmi toutes les facteurs possibles qui peuvent contribuer à ces deux objectifs, la température est une caractéristique importante. Ces dernières années, les caméras infrarouges ont fait d'énormes progrès. Leur prix a été réduit de façon significative tandis que les progrès techniques ont fortement augmenté. Ces technologies sont des candidats sérieux pour détecter les changements de température dans les troubles du pied diabétique. Toutes ces raisons font que l'intérêt de la mesure de la température du pied devient de plus en plus un sujet actif comme le prouvent les deux sections suivantes.

La température de la voute plantaire est proche de 32°C. Pour une personne saine (pas de diabète), la distribution de la température de la voute plantaire n'est pas uniforme et montre ce que l'on appelle une forme de papillon [Chan 1991]. La température du pied diabétique est

plus complexe du à des problèmes de thermorégulations liés à la neuropathie, à l'ischémie, et également en des inflammations. Aucune forme typique comme celle du papillon n'existe chez les personnes normales mais plusieurs formes peuvent être observées. Dans les deux cas (diabete et non diabete), les variations possibles de la température plantaire sont généralement inférieures à 4 ° C. Dans un travail récent, [Nagase, 2012] étudie les variations de température plantaire liée à l'ischémie. Il conclut qu'une plus grande variation est présente chez les patients diabétiques que chez les sujets sains. Une autre façon d'évaluer les problèmes de thermorégulation est d'effectuer un test de stress au froid [Balbino, 2012]. La différence de température avant et après le stress dû au froid s'avère intéressant dans le diagnostic précoce de la neuropathie diabétique.

D'autre part, les études montrent qu'il existe une relation entre l'augmentation de la température plantaire et les complications du pied chez les diabétiques : une augmentation de la température peut être présente jusqu'à une semaine avant qu'un ulcère du pied ne se produise [Armstrong, 2007]. La température locale du pied droit et gauche en chaque point ne diffère généralement pas de plus de 1°C. Une différence de température supérieure à 2.2°C est considérée comme anormale. La détection de cette augmentation de température entre les deux pieds associée à un traitement adéquat peut réduire l'incidence de l'ulcère du pied par 3. Ce résultat d'une importance majeure fait que plusieurs équipes de recherche, parfois associés à une entreprise privée, ont proposé ou testé sur des appareils domestiques pour surveiller la température du pied [Roback, 2010]. Ces dispositifs doivent être à faible coût et facile à utiliser. Cependant, aucun système déjà proposé ne semble être largement utilisé parce qu'ils n'ont pas satisfait aux exigences précédentes. Aucun d'entre eux n'est basé sur une caméra thermique. Une des conclusions de [Roback, 2010] était de dire que les caméras infrarouges sont des candidats sérieux pour détecter à la maison, dans un proche avenir, ces changements thermiques du pied diabétique.

Objet de la thèse

L'objectif général de la thèse concerne le domaine du pied diabétique et suit les deux directions de recherche déjà mentionnées : améliorer le diagnostic précoce du pied diabétique et réduire les ulcères dans le pied diabétique. Elle sera basée sur l'analyse des images thermiques infrarouges de la voute plantaire. Les directions possibles sont doubles :
• Développer de nouvelles stratégies pour améliorer le diagnostic précoce du pied diabétique dans les hôpitaux fondée sur l'analyse des images thermiques,
• Concevoir et tester un système domestique pour surveiller la température du pied à l'aide d'une caméra infrarouge.

Le deuxième objectif nécessitera l'élaboration d'un système dédié à l'aide d'une caméra infrarouge pour mesurer la température de la surface plantaire chez soi. Développer et tester un tel dispositif dans un temps très limité est difficile. Il n'a pas été retenu. Ce travail sera principalement consacré au premier objectif et la thèse est intitulée :

Diagnostic précoce du pied diabétique à base d'images thermiques

La première étape du projet sera de comprendre parfaitement les variations de température qui se produisent dans le pied diabétique avant qu'un ulcère apparaisse. Les variations de température du pied sont multifactorielles. Elles sont principalement liés à des problèmes de circulation sanguine, des problèmes neuropathiques, et à l'infection.

Organisation du rapport de thèse

Ce rapport de thèse est structuré comme suit.

Dans le chapitre 2, la définition du diabète et de ses diverses formes, sera donné. Les maladies du pied diabétique seront présentées. L'intérêt de l'approche thermique dans ces cas sera démontré.

Le chapitre 3 sera consacré à l'utilisation des images thermiques dans divers domaines, et particulièrement les applications dans le domaine biomédical. Les travaux connexes pour le pied diabétique seront montrés et discutés. La dernière partie sera consacrée au choix de la caméra thermique pour le projet.

De l'analyse précédente, le chapitre 4 décrit le protocole d'acquisition d'image, et les méthodes de traitement d'images développées dans ce travail pour évaluer les variations thermiques de la voute plantaire.

Le chapitre 5 présente une étude clinique transversale où plusieurs images thermiques du pied diabétique seront analysées.

Enfin, une conclusion sera donnée et les perspectives de ce travail seront proposées. Quatre annexes sont également présentes : la première est liée à la technologie des capteurs infrarouges, la seconde à la convention médicale relative à ce travail à l'hôpital Dos de Mayo à Lima, la troisième montre la base de données d'image de l'étude médicale et la dernière concerne les paramètres calculés à partir des images thermiques.

Contexte général

Luis Vilcahuaman est un enseignant à la Pontificia Universidad Catolica del Peru à Lima. En 2008, il a commencé une thèse de doctorat à l'Université d'Orléans, sous la direction du Professeur Rachid Harba, et avec l'aide de Raphaël Canals, Maître de Conférences. Le projet implique également l'hôpital Dos de Mayo à Lima et l'hôpital Orléans. Au cours de son doctorat, Luis Vilcahuaman a reçu le soutien des deux universités ainsi que celui de l'Ambassade française au Pérou (bourse Raul Porras Barrenechea).

Récemment, l'Université d'Orléans et la Pontificia Universidad Javeriana de Bogota (Martha Zaquera, Maître de Conférences) ont obtenu un soutien financier par le biais d'un projet ECOS-Nord pour continuer à travailler sur les images thermiques du pied diabétique. Martha Zaquera est fortement impliquée dans le projet. Il concerne également l'hôpital de l'Université Javeriana.

CHAPTER II

2. Diabetes and diabetic foot

In this chapter, the diabetes and its related complications will be of interest. A focus on diabetic foot will be presented, that will lead to the definition of the object of the thesis.

2.1. Fundamentals of diabetes

2.1.1. Definition and types of diabetes

Diabetes mellitus (DM), or simply, diabetes, is a group of diseases characterized by high blood glucose levels that result from defects in the body's ability to produce and/or use insulin. Diabetes is a disorder of metabolism, the way the body uses digested food for growth and energy. Most of the food that people eat is broken down into glucose, the form of sugar in the blood. Glucose is the main source of fuel for the body. After digestion, glucose passes into the bloodstream, where it is used by cells for growth and energy. For glucose to get into cells, insulin must be present. Insulin is a hormone produced by the pancreas, a large gland behind the stomach. When people eat, the pancreas automatically produces the right amount of insulin to move glucose from blood into the cells. In people with diabetes, however, the pancreas either produces little or no insulin, or the cells do not respond appropriately to the insulin that is produced. Glucose builds up in the blood, overflows into the urine, and passes out of the body in the urine. Thus, the body loses its main source of fuel even though the blood contains large amounts of glucose (hyperglycemia). The normal blood glucose considers the range (70 − 120 mg/dl); it is named normoglycemia [Seibel, 2008].

In hospital, hyperglycemia is defined as any glucose value greater than 140 mg/dl [Moghissi, 2009]. Hyperglycemia occurs not only in patients with known diabetes but also in those with previously undiagnosed diabetes and others with "stress hyperglycemia" [Dungan, 2009].

Formally, diabetes is a group of metabolic diseases characterized by hyperglycemia resulting from defects in insulin secretion, insulin action, or both. The chronic hyperglycemia of

diabetes is associated with long-term damage, dysfunction and failure of different organs, especially eyes, kidneys, foot, nerves, heart and blood vessels [ADA, 2012].

The vast majority of cases of diabetes fall into two broad etiopathogenetic categories. The first category, type 1 diabetes, is due to an absolute deficiency of insulin secretion. Type 1 diabetes is usually diagnosed in children and young adults, and was previously known as juvenile diabetes. Individuals at increased risk of developing this type of diabetes can often be identified by serological evidence of an auto-immune pathologic process occurring in the pancreatic islets and by genetic markers. In the second category, type 2 diabetes, the cause is a combination of resistance to insulin action and an inadequate compensatory insulin secretory response. In this project, we will only study type 2 diabetes, which is by far the most important one in number of involved persons (90–95% of DM). We will also focus on foot ulcer that may occur following type 2 diabetes.

In type 2 diabetes, a degree of hyperglycemia is sufficient to cause pathologic and functional changes in various target tissues, but without clinical symptoms. It may be present for a long period of time before diabetes is detected. During this asymptomatic period, it is possible to demonstrate an abnormality in carbohydrate metabolism by measurement of plasma glucose in the fasting state or after a challenge with an oral glucose load.

Stages / Types	Normoglycemia	Hyperglycemia			
	Normal glucose regulation	Impaired Glucose Tolerance or Impaired Fasting Glucose (Pre-Diabetes)	Diabetes Mellitus		
			Not insulin requiring	Insulin requiring for control	Insulin requiring for survival
Type 1*					
Type 2					
Other Specific Types**					
Gestational Diabetes **					

Figure 2.1: Disorders of glycemia: etiologic types and stages from [ADA, 2012]
* Even after presenting in ketoacidosis, these patients can briefly return to normoglycemia without requiring continuous therapy (i.e., "honeymoon" remission);
** In rare instances, patients in these categories (e.g., Vacor toxicity, type 1 diabetes presenting in pregnancy) may require insulin for survival.

The degree of hyperglycemia (if any) in type 1 and 2 diabetes may change over time, depending on the extent of the underlying disease process (Fig. 2.1). A disease process may be present but may not have progressed far enough to cause hyperglycemia. The same disease process can cause impaired fasting glucose (IFG) and/or impaired glucose tolerance (IGT) without fulfilling the criteria for the diagnosis of diabetes. In some individuals with diabetes, adequate glycemic control can be achieved with weight reduction, exercise, and/or oral glucose lowering agents. These individuals therefore do not require insulin. Other individuals who have some residual insulin secretion but require exogenous insulin for adequate glycemic control can survive without it. Individuals with extensive b-cells destruction and therefore no residual insulin secretion require insulin for survival. The severity of the metabolic abnormality can progress, regress, or stay the same. Thus, the degree of hyperglycemia reflects the severity of the underlying metabolic process and its treatment more than the nature of the process itself.

The prevalence of Diabetes Mellitus (DM) in the world is increasing dramatically and is a serious public health problem, especially for its devastating late manifestations, which determines a high morbidity and mortality. In 1995, the World Health Organization has estimated the prevalence of DM in the world at 4% and the number of diabetics 135 millions. In 2009, 347 million were suffering this disease, and 500 millions are expected in 2030, corresponding to a prevalence of 5.4%. In 2004, 3.4 millions died from diabetes. Diabetes is the seventh cause in dying in the world and especially affects poor countries. The prevalence of DM in Peru was estimated at 5% for 1995 and in 2025 there will be 7%, with respectively a total of 637,000 and 1,747, 000 diabetics [Neyra, 2012].

2.1.2. Diabetes complications

Patients with diabetes have an increased incidence of atherosclerotic cardiovascular, peripheral arterial and cerebrovascular disease. Hypertension and abnormalities of lipoprotein metabolism are often found in people with diabetes. In addition long-term complications of diabetes include nephropathy leading to renal failure, retinopathy with potential loss of vision, peripheral neuropathy with risk of foot ulcers, amputations, Charcot disease, and autonomic neuropathy causing gastrointestinal, genitourinary and cardiovascular symptoms.

I.   *Cardiovascular Disease*

Cardiovascular Disease (CVD) is the major cause of morbidity and mortality for individuals with diabetes and the largest contributor to the direct and indirect costs of diabetes. The

common conditions coexisting with type 2 diabetes (e.g., hypertension and dyslipidemia) are clear risk factors for CVD, and diabetes itself confers independent risk. Numerous studies have shown the efficacy of controlling individual cardiovascular risk factors in preventing or slowing CVD in people with diabetes. Large benefits are seen when multiple risk factors are addressed globally [Buse et al., 2007], [Gaede et al., 2008]. There is evidence that measures of 10-year coronary heart disease (CHD) risk among U.S. adults with diabetes have improved significantly over the past decade [Ford, 2011].

a. Hypertension

Hypertension is a common comorbidity of diabetes, affecting the majority of patients, with prevalence depending on type of diabetes, age, obesity, and ethnicity. Hypertension is a major risk factor for both CVD and microvascular complications. In type 1 diabetes, hypertension is often the result of underlying nephropathy, while in type 2 diabetes it usually coexists with other cardiometabolic risk factors.

Recommendations for screening and diagnosis: blood pressure should be measured at every routine diabetes visit. Patients found to have systolic blood pressure (SBP) ≥ 130mmHg or diastolic blood pressure (DBP) ≥ 80 mmHg should have blood pressure confirmed on a separate day. Repeated SBP ≥ 130mmHg or DBP ≥ 80 mmHg confirms a diagnosis of hypertension.

b. Dyslipidemia/lipid

Patients with type 2 diabetes have an increased prevalence of lipid abnormalities, contributing to their high risk of CVD. For the past decade or more, multiple clinical trials demonstrated significant effects of pharmacologic (primarily statin) therapy on CVD outcomes in subjects with CHD and for primary CVD prevention. Subanalyses of diabetic subgroups of larger trials [Pyõrãlä et al., 1997] [Collins et al., 2003] [Goldberg et al., 1998] [Shepherd et al., 2006] [Sever et al., 2005] and trials specifically in subjects with diabetes [Knopp et al., 2006] [Colhoun et al., 2004] showed significant primary and secondary prevention of CVD events +/- CHD deaths in diabetic populations. Similar to findings in nondiabetic subjects, reduction in "hard" CVD outcomes (CHD death and nonfatal myocardial infarct (MI)) can be more clearly seen in diabetic subjects with high baseline CVD risk (known CVD and/or very high LDL cholesterol levels), but overall the benefits of statin therapy in people with diabetes at moderate or high risk for CVD are convincing (LDL = low-density lipoproteins). Low levels of HDL cholesterol (HDL = high density lipoproteins), often associated with elevated

triglyceride levels, are the most prevalent pattern of dyslipidemia in persons with type 2 diabetes. However, the evidence base for drugs that target these lipid fractions is significantly less robust than that for statin therapy [Singh et al., 2007]. Nicotinic acid has been shown to reduce CVD outcomes, although the study was done in a nondiabetic cohort. Gemfibrozil has been shown to decrease rates of CVD events in subjects without diabetes and in the diabetic subgroup of one of the larger trials. However, in a large trial specific to diabetic patients, fenofibrate failed to reduce overall cardiovascular outcomes [Keech et al., 2005].

c. Coronary Heart Disease (CHD)

Screening for coronary artery disease (CAD) is reviewed in a recently updated consensus statement [Bax et al., 2007]. To identify the presence of CAD in diabetic patients without clear or suggestive symptoms, a risk factor–based approach to the initial diagnostic evaluation and subsequent follow-up has intuitive appeal. However, recent studies concluded that using this approach fails to identify which patients with type 2 diabetes will have silent ischemia on screening tests [Scognamiglio et al., 2006].

Candidates for cardiac testing include those with 1) typical or atypical cardiac symptoms and 2) an abnormal resting ECG. The screening of asymptomatic patients remains controversial. Intensive medical therapy, which would be indicated anyway for diabetic patients at high risk for CVD, seems to provide equal outcomes to invasive revascularization, which raises questions of how screening results would change management [Frye et al., 2009].

II. *Nephropathy (renal disease)*

Diabetic nephropathy occurs in 20–40% of patients with diabetes and is the single leading cause of end-stage renal disease (ESRD). Persistent albuminuria in the range of 30–299 mg/24 h (microalbuminuria) has been shown to be the earliest stage of diabetic nephropathy in type 1 diabetes and a marker for development of nephropathy in type 2 diabetes. Microalbuminuria is also a well-established marker of increased CVD risk [Klausen et al., 2004]. Patients with microalbuminuria who progress to macroalbuminuria ($\geq$ 300 mg/24 h) are likely to progress to ESRD. However, some interventions have been demonstrated to reduce the risk and slow the progression of renal disease.

Intensive diabetes management with the goal of achieving near-normoglycemia has been shown in large prospective randomized studies to delay the onset of microalbuminuria and the progression of micro- to macroalbuminuria in patients with type 1 and type 2 diabetes [Ismail-

Beigi et al., 2010]. The United Kingdom Prospective Diabetes Study (UKPDS) provided strong evidence that control of blood pressure can reduce the development of nephropathy. In addition, large prospective randomized studies in patients with type 1 diabetes have demonstrated that achievement of lower levels of systolic blood pressure SBP (<140mmHg) resulting from treatment using angiotensin-converting-enzyme (ACE) inhibitors provides a selective benefit over other antihypertensive drug classes in delaying the progression from micro- to macroalbuminuria and can slow the decline in glomerular filtration rate (GFR) in patients with macroalbuminuria. In type 2 diabetes with hypertension and normoalbuminuria, renin-angiotensin system (RAS) inhibition has been demonstrated to delay onset of microalbuminuria in two studies [Haller et al., 2011]. In the latter study, there was an unexpected higher rate of fatal cardiovascular events with olmesartan among patients with preexisting CHD.

III. Retinopathy (eyes disease)

Diabetic retinopathy is a highly specific vascular complication of both type 1 and type 2 diabetes, with prevalence strongly related to the duration of diabetes. Diabetic retinopathy is the most frequent cause of new cases of blindness among adults aged 20–74 years. Glaucoma, cataracts, and other disorders of the eye occur earlier and more frequently in people with diabetes.

In addition to duration of diabetes, other factors that increase the risk or are associated with retinopathy include chronic hyperglycemia, nephropathy, and hypertension. Intensive diabetes management with the goal of achieving near normoglycemia has been shown in large prospective randomized studies to prevent and/or delay the onset and progression of diabetic retinopathy [Chew et al., 2010]. Lowering blood pressure has been shown to decrease the progression of retinopathy, although tight targets (systolic < 120 mmHg) do not impart additional benefit. Several case series and a controlled prospective study suggest that pregnancy in type 1 diabetic patients may aggravate retinopathy [Fong et al., 2004]; laser photocoagulation surgery can minimize this risk.

IV. Neuropathy (autonomic and peripheral)

The diabetic neuropathies are heterogeneous with diverse clinical manifestations. They may be focused or diffuse. Most common among the neuropathies are chronic sensorimotor diabetic peripheral neuropathy (DPN) and autonomic neuropathy. Although DPN is a diagnosis of exclusion, complex investigations to exclude other conditions are rarely needed.

The early recognition and appropriate management of neuropathy in the patient with diabetes is important for a number of reasons: 1) nondiabetic neuropathies may be present in patients with diabetes and may be treatable; 2) a number of treatment options exist for symptomatic diabetic neuropathy; 3) up to 50% of DPN may be asymptomatic and patients are at risk for insensate injury to their feet; 4) autonomic neuropathy and particularly cardiovascular autonomic neuropathy is associated with substantial morbidity and even mortality. Specific treatment for the underlying nerve damage is currently not available, other than improved glycemic control, which may modestly slow progression [Ismail-Beigi, 2010] but not reverse neuronal loss. Effective symptomatic treatments are available for some manifestations of DPN [Bril et al., 2011] and autonomic neuropathy.

V. *Diabetic foot as diabetic complication*

General and specific information will be developed in the following subchapter 2.2 for diabetic foot complications.

2.2. Diabetic Foot

2.2.1. General information on diabetic foot

Foot complications are among the most serious and costly complications of diabetes mellitus (DM). Amputation of the lower extremity or part of it is usually preceded by a foot ulcer. A strategy that includes prevention, patient and staff education, multidisciplinary treatment of foot ulcers, and close monitoring can reduce amputation rates by 49–85% [Apelqvist, 2008]. Therefore, several countries and organizations, such as the World Health Organization and the International Diabetes Federation, have set goals to reduce the rate of amputations by up to 50% [Bakker et al., 2012].

As the longevity of the population increases, the incidence of diabetes-related complications also increases [Andersen and Roukis, 2007]. Among the complications of diabetes are foot problems, the most common cause of non-traumatic limb amputation [Boulton et al, 2005]. The feet of people with diabetes can be affected by neuropathy, peripheral arterial disease, foot deformity, infections, ulcers and gangrene.

The International Diabetes Federation decided in 2005 to start a campaign to prevent diabetic foot, whereas it has been estimated that every 30 seconds a lower limb is lost somewhere in the world as a result of diabetes [IDF, 2005]. Also, about 50% of people who undergo non-traumatic amputations of the lower limb suffer diabetes, and diabetic patients have between 12 and 22 times greater risk of amputation of lower limbs compared with non-diabetics [Fosse et al., 2009].

According to [Torres et al., 2012] for the year 2000, the approximate number of Peruvians with diabetes in 2011 was 942.000 and 420.000 of them were unaware of having the disease. The factors that contribute to diabetic foot disease, such as peripheral neuropathy and peripheral vascular disease, are present in more than 10% of people when being diagnosed with type 2 DM. It is estimated that between 15 to 25% of patients with diabetes eventually will develop foot ulcer.

In Peru, research has been conducted to describe the characteristics of patients with diabetic foot disease. [Alcántara et al., 1999] conducted a study of patients admitted for diabetic foot in the Dos de Mayo Hospital (Lima) between 1989 and 1997, finding that a total of 206 patients underwent limb amputation, of them 69.1% suffered major amputation and 31% lower amputation. They also found that 10% of patients suffered re-amputation to 2.2 years, which it is a percentage less than 40% reported by other authors.

Diabetic foot problems have a significant financial impact through outpatient costs, increased bed occupancy and prolonged stays in hospital. In addition, diabetic foot problems have a significant impact on the quality of life; for example, reduced mobility that may lead to loss of employment, depression and damage to or loss of limbs. Diabetic foot problems require urgent attention. A delay in diagnosis and management increases morbidity and mortality and contributes to a higher amputation rate. The common clinical features of diabetic foot problems include infection, osteomyelitis, neuropathy, peripheral arterial disease and Charcot arthropathy. Laboratory evaluations include blood tests, different imaging techniques, microbiological and histological investigations, but currently there is no guidance on which tests are the most accurate and cost effective. The primary objective in managing diabetic foot problems is to promote mobilization. This involves managing both medical and surgical problems and involving a range of medical experts in related fields [NICE, 2012].

Despite the publication of strategies on commissioning specialist services for the management and prevention of diabetic foot problems in hospital ('Putting feet first', Diabetes UK 2009; 'Improving emergency and inpatient care for people with diabetes', Department of Health 2008), there is variation in practice in the inpatient management of diabetic foot problems. This variation is due to a range of factors, including differences in the organization of care between patients' admission to an acute care setting and discharge. This variability depends

on geography, individual trusts, individual specialties (such as whether the service is managed by vascular surgery, general surgery, orthopedics, diabetologists or general physicians) and the availability of podiatrists with expertise in diabetic foot disease.

Although the spectrum of foot lesions varies in different regions of the world, the pathways to ulceration are probably identical in most patients. Diabetic foot lesions frequently result from two or more risk factors occurring together. In the majority of patients, diabetic peripheral neuropathy plays a central role: up to 50% of people with type 2 diabetes have neuropathy and at-risk feet. Neuropathy leads to an insensitive and sometimes deformed foot, often with an abnormal walking pattern. In people with neuropathy, minor trauma – caused, for example, by ill-fitting shoes, walking barefoot, or an acute injury – can precipitate a chronic ulcer. Loss of sensation, foot deformities, and limited joint mobility can result in abnormal biomechanical loading of the foot. Thickened skin (callus) forms as a result of this loading. This leads to a further increase of the abnormal loading and, often, subcutaneous hemorrhage.

Whatever the primary cause, the patient continues walking on the insensitive foot, impairing subsequent healing (Figure 2.2). Peripheral vascular disease, usually in conjunction with minor trauma, may result in a painful, purely ischaemic foot ulcer. However, in patients with both neuropathy and ischaemia (neuroischaemic ulcer), symptoms may be absent, despite severe peripheral ischaemia. Microangiopathy should not be accepted as a primary cause of an ulcer. See Figure 2.2 for a visual explanation of the ulceration mechanism, and Figure 2.3 showing an illustration of foot ulcers.
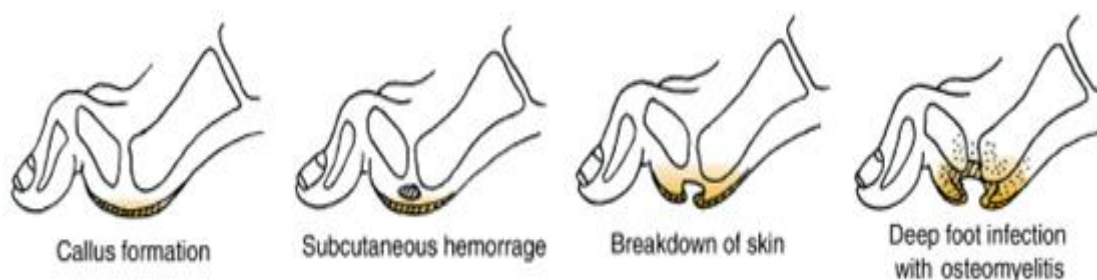
Figure 2.2: Foot ulcer due to repetitive stress from [Bakker et al., 2012]

Figure 2.3: An illustration of foot ulcers

There are areas where it is very likely that a foot ulcer occurs. There are named areas at risk as illustrates figure 2.4. Detecting problems in these zones is of great interest.

The smallest areas at risk are more or less a circle of 1cm of diameter. This characteristic is of importance for systems build to detect problems in diabetic foot.

Figure 2.4: Areas at risk on the foot from [Bakker et al., 2012]

The key element for the diabetic foot diagnosis is the regular examination of the diabetic population by a specialized medical doctor in hospital.

I.   Diabetic foot examination

All people with diabetes should be examined at least once a year by a specialized medical doctor in a hospital for potential foot problems following items show in table 2.1. Patients with demonstrated risk factor(s) should be examined more often – every 1–6 months. The absence of symptoms does not mean that the feet are healthy; the patient might have neuropathy, peripheral vascular disease, or even an ulcer without any complain. The patient's feet should be examined with the patient lying down and standing up, and their shoes and socks should also be inspected.

Table 2.1: Examination for potential foot problems

History and examination	
History	Previous ulcer/amputation, previous foot education, social isolation, poor access to healthcare, bare-foot walking.
Neuropathy	Symptoms, such as tingling or pain in the lower limb, especially at night.
Vascular Status	Claudicating, rest pain, pedal and tibia pulses, pain while walking, ankle/brachial pressure
Skin	Color, temperature, edema
Bone / Joint	Deformities (e.g. claw toes, hammer toes) or bony prominences
Footwear / Socks	Assessment of both inside and outside
Sensory Loss	
Sensory loss due to diabetic polyneuropathy can be assessed using the following techniques:	
Pressure perception	Semmes-Weinstein monofilaments. The risk of future ulceration can be determined with a 10 g monofilament (see text below)
Vibration perception	128 Hz tuning fork (hallux)
Discrimination	Pin prick (dorsum of foot, without penetrating the skin)
Tactile sensation	Cotton wool (dorsum of foot)
Reflexes	Achilles tendon reflexes

A very important exam is the 10g monofilament one. Such a tool can be seen in Figure 2.4. This simple and efficient device is worldwide used to estimate the sensory loss in the plantar foot surface. The 10g monofilament is randomly applied to the point at risk as defined in Figure 2.5. The patient must immediately answer by yes or no (yes: he fells something, no: he does not fell something).

The 10g monofilament is also applied to the dark spots. "Dark spots" are little areas with a dark color that could be present on the plantar foot surface. These dark spots can be the initial sign of ulcer. Sometimes it is simply a discoloration of the skin.

II.   Diagnosis of diabetic foot

From this analysis, a by-risk classification is given by the medical doctor. The risk here means the risk of developing a foot ulcer. This classification is not the same in every country. In France, for example, the classification used in most French hospitals is the following:

- Grade 0: no neuropathy, no ischemia, possible foot deformations independent of the diabetes,
- Grade 1: small neuropathy defined as the absence of sensation at least one point of the points at risk of the feet,
- Grade 2: neuropathy + foot deformation and/or ischemia defined as the absence of 2 pedal pulses,
- Grade 3: previous amputations or ulcers that lasted more than 3 months.

A grade 0 means that the patient has no diabetic foot. Any other grade number means diabetic foot patient.

The Diabetic Foot Unit in Hospital National Dos de Mayo (HNDM), Lima, Peru, was created in 2008, for the prevention of ulcers among diabetic patients and prompt handling of injuries; the medical study in this work will be done in collaboration with this hospital. The by-risk classification in this institution is as follows (see Table 2.2 for details):

- Low risk,
- Medium risk,
- High risk.

From the medical analysis, another classification, named by-disease classification, is given by the medical doctor in HNDM:

- Healthy (no ischemia or neuropathy),
- Ischemia,
- Neuropathy,
- Mixed (ischemia + neuropathy).

Details are given in Table 2.3.

Figure 2.5: A 10g monofilament

Table 2.2: By-risk classification of diabetic foot in HNDM (Lima, Peru)

Low risk patient: meets all of the following:	Medium risk patient: one or more of the following:	High risk patient: one or more of the following:
• The patient perceives the monofilament at all points of the points at risk • No previous ulcer • The patient shows no severe deformity • Pedal pulses present • No amputation	• Lack of perception of the monofilament in one or more of dark spots • Difficult perception of the tibia pulse • Shows a deformity • Shows callus formation	• Lack of perception of monofilament in one or more of points at risk • Pedal pulses absent • The patient has two or more deformities • The patient has a history of foot ulcer • The patient shows previous amputation • Patient with foot ischemic or mixed
Next appointment in 12 months	Next appointment from 3 to 6 months	Next appointment from 1 to 3 months

Table 2.3: By-disease classification of diabetic foot in HNDM (Lima, Peru)

Healthy patient	Ischemia patient	Neuropathy patient	Mixed patient
• No ischemia or neuropathy	• Difficult perception of tibial pulses • Pedal pulses absent • Ankle/brachial pressure • The patient perceives the monofilament at all points of the points at risk	• Lack of perception of monofilament in one or more of points at risk • Vibration sensibility • Pedal and tibial pulses present • Problems in Achilles and/or plantar refex	• Ischemia and neuropathy

The two classification approaches (by-risk and by-disease) will be used in the medical study.

In the early stages of the disease, the signs of possible ischemia or neuropathy are subtle. In case of doubt, a Doppler analysis can be done in the case of ischemia. New technologies are required to improve this early diagnosis. Among all possible features, temperature is an important characteristic in diabetic foot as shown in the next section.

2.2.2. Thermal approach in diabetic foot

Diabetic foot complications are associated with substantial costs and loss of quality of life. In many cases, development and deterioration of diabetic foot disorders can be avoided or substantially delayed with adequate treatment: a risk assessment of diabetic patients and determination of foot status, provided at an early stage. Temperature can be of interest in this case.

The current healthcare practice for temperature assessment is manual palpation of foot temperature. However, the increase in temperature is usually too subtle to be detected manually [Murff et al., 1998]. Mapping of the foot temperature with a thermometer is rather time consuming, and the invention of a thermographic instrument for temperature imaging of the entire foot has therefore been an attractive option.

For a control person the temperature distribution in the plantar foot is a bilateral butterfly pattern [Chan, 1991]. Plantar foot temperature varies in diabetic foot due to thermoregulations

problems related to neuropathy, ischemia, or infection. No typical form exists as in normal persons but several shapes can be observed. In both cases (controls and cases), the possible variations of the plantar foot temperature are usually lower than 4°C. In a recent work, [Nagase, 2012] studies the variations of plantar foot temperature linked to ischemia. He concludes that a wider variation is present in diabetic patients than in control subjects. Another way to estimate thermoregulation problems is to perform a cold stress test [Balbino, 2012]. The temperature difference before and after the cold stress is shown to be interesting in the early diagnosis of diabetic neuropathy.

It has been established that increased temperature may be present up to a week before a foot ulcer occurs [Sun et al., 2006] [Armstrong et al., 2007]. In this early stage of the disease, patients seldom feel pain because of neuropathic sensory loss, which indicates that increased temperature can be a useful predictive sign of foot ulceration and subclinical inflammation of the feet. However, in order to define 'increased temperature', a standardized reference temperature is required that can be employed for a specific risk category of patients. Foot temperature varies between patients, and depends on ambient temperature and level of activity. The most frequently used reference is therefore a corresponding area on the contralateral foot. Temperatures of corresponding areas of the right and left foot do not usually differ by more than 1°C, and a temperature difference of more than 2.2°C (4°F) is considered abnormal [Armstrong et al., 1996] [Armstrong et al., 2003] [Armstrong et al., 2006]. Also, in conditions that lead to higher or lower foot temperatures, such as arteriovenous shunts and atherosclerosis, the temperature change is often evenly distributed between the feet [Papanas et al., 2009]. Consequently, there seems to be a rationale for determining foot temperatures in diabetic patients.

The subject of foot temperature assessment in diabetes has been investigated by several authors, and in a review by [Bharara et al., 2006], four feasible techniques were identified, three of which have now been developed into commercial products by different inventors:

1. Liquid crystal thermography (LCT),
2. Temperature sensors integrated into a weighing scale,
3. Scanning with infrared (IR) thermometer
4. Infrared camera (this technology is discussed in appendix A).

Liquid crystal thermography

The ideal instrument for temperature scanning should preferably produce temperature readings of the entire foot in one measurement procedure. Several different inventions have been presented, such as arrays of IR thermosensors, IR camera systems, shoes that measure

temperature and LCT, but none so far have been diffused into widespread practice. The technology that seems to be in the most advanced stage is LCT, but the literature review found only two commercial products within this field of innovations, the Spectra Sole Pro 1000 [18], which has been available for some time, and the more recent TempStat™ [19].

The LCT technology gives information regarding the warmth distribution of the foot through a colored foot imprint on a plate comprised of layers of encapsulated thermochromic liquid crystals. Warmth is transferred from the foot and accumulated in the plate, which gives rise to a spectrum of colors depending on the temperature. The image remains for a few minutes and then slowly fades away. The colors of the image can be compared with a template from which corresponding temperatures can be read. There is also an option for digital storage of images, but currently there is no digital registration for the measured temperatures.

SpectraSole Pro 1000 was developed for preventive diagnostics and for the purpose of following the healing of foot complications. The target users are professionals in multidisciplinary diabetes teams. Results from a feasibility study of this instrument show that it is easy to use and that it gives additional information that could lead to more patients getting an adequate off loading and assessment of their feet [Roback, 2009]. The instrument is intended to be used together with standard inspections of the feet. The invention has so far had a limited experimental use in diabetes units in a handful of countries. TempStat is intended for personal homecare in combination with regular standard examinations in professional care. Visual signs of the onset of complications can be detected both via temperature images and a magnification mirror integrated in the instrument. No clinical studies were found in the literature, but a patient survey by Frykberg *et al.* (2009) has been conducted to obtain an estimate of the ability of TempStat to assist in self-examinations of the feet [Fryberg, 2009]. Results show that the instrument clearly visualizes hot spots and that the readings have good correlation with point measurements with IR thermometer.

Temperature-sensing weighing scale

The Thermoscale® was invented in Taiwan, and a patent application was filed in the USA in 2006. It is currently available as a personal self-care device. It can be described as a body-weighing scale with integrated temperature-sensing thermistors, two under each foot. The scale also has a body fat measurement function [Manichand, 2013].

Scanning of foot temperature with IR thermometer

Several studies have shown that temperature is an important parameter in the assessment of the diabetic foot, but few have investigated what could be gained in fewer complications and better health. However, three randomized trials [Lavery et al., 2004 and 2007], and

[Armstrong et al., 2007] all indicate that, at home, monitoring of foot temperature would significantly limit the rates of re-ulceration in diabetes [Lavery, Higgins et al, 2007] [Armstrong, Holtz et al, 2007]. The instrument used in the trials was the TempTouch® Dermal Thermometer, which is an IR thermometer for self-inspection of the feet [Constantinides, 2000]. Foot temperature should be measured daily on six foot sites and recorded in a logbook. In case of a temperature difference of more than 2.2 °C between corresponding sites of the right and left foot, the users are advised to decrease their activity level and contact the diabetes nurse immediately.

There is also an option to use traditional IR camera systems to assess foot temperature [Sun et al., 2006] [Bharara et al., 2006]. However, none of these 4 technologies has been adopted in standard healthcare.

Patient responsibility is also a factor that determines the course of the disease. Intensive treatment must be applied at a stage when the patients' perceptions of the indicated complication are usually vague. Insufficient understanding of the disease and low adherence to treatment is a well-recognized problem in diabetes care, and patient education and self-care must therefore be prioritized.

A conclusion was drawn that regular temperature monitoring of diabetic feet has a potential to reduce the incidence of foot ulcers, assuming that diagnosed foot complications are followed up and adequately treated. Temperature monitoring could be a complementary diagnostic method in the prevention of major foot complications, but cannot replace any of the current steps in modern diabetes care. Adoption of temperature monitoring in standard care may lead to a more frequent referral of patients from primary care to specialists, as further imaging studies will be needed to determine the cause of an increased temperature. Early diagnosis and early treatment is crucial for the healing of diabetic foot lesions and resources for early interventions must therefore be available to take care of a higher number of suspected foot complications [Roback, 2010].

2.3. Goal of the thesis

2.3.1. General Objective

The aim of this project is to evaluate the potential of thermography for early diagnosis of type 2 diabetic foot, from images obtained with an infrared camera. Our expectation is to find that the temperature could help in the early diagnosis of diabetic foot in hospitals, and can help to prevent the occurrence of a foot ulcer.

Main advantages of thermography are that it is simple to use, non-invasive, contactless, non-irradiant, and fast.

2.3.2. Specific Objectives

Four objectives have been defined:

- Develop a robust protocol for thermographic imaging acquisition (including the choice of the infrared camera) for use in a clinical setting for diagnosis and monitoring of diabetic foot, knowing that it should be a simple, effective and low cost method to produce images of sufficient quality for the corresponding clinical analysis.

- Develop a software tool for an automatic analysis of the temperature of the right and left foot plantar surface. This software will measure global temperature of the foot surface (mean and variance) of each foot, and also the difference of the right and left foot temperature. Differences greater than 2.2°C will by pointed out.

- Determine the recruitment protocol of patient for a transversal clinical study, given informed consent of patients and hospital agreement.

- Conduct a transversal clinical study in order to find the correlation between the temperature parameters of the plantar foot with the medical classification to help in the early diagnosis of diabetic foot, and/or to prevent the occurrence of a foot ulcer.

2.4. Conclusion

In this chapter, we have considered diabetes and its related complications. After focusing on diabetic foot, we have studied in details the way used in the Dos de Mayo Hospital to accomplish the diagnosis of type 2 diabetic foot. Two possible classifications are present: the risk classification, and the disease classification.
The temperature could be useful in the early diagnosis of diabetic foot. The main research studies and used technologies were described. This leads us to the definition of the object of the present thesis: the early diagnosis of diabetic foot using thermal images.

2.5 Le diabète et le pied diabétique (in french language)

Le diabète correspond à un ensemble de maladies métaboliques caractérisées par des niveaux élevés de glucose dans le sang qui résultent de défauts dans la capacité du corps à produire et / ou à utiliser l'insuline. Le diabète est un trouble du métabolisme, de la façon dont le corps utilise la nourriture digérée pour la croissance et l'énergie. Les aliments que les gens mangent sont décomposés en glucose, sous forme de sucre dans le sang. Le glucose est la source principale de carburant pour le corps. Après digestion, le glucose passe dans le sang où il est utilisé par les cellules pour la croissance et l'énergie. Pour que le glucose puisse pénétrer dans les cellules, l'insuline doit être présente. S'il y a manque ou absence d'insuline, le glucose s'accumule dans le sang, déborde dans l'urine par laquelle il est évacué à l'extérieur du corps. Ainsi le corps perd sa principale source d'énergie, même si le sang contient de grandes quantités de glucose (hyperglycémie).

L'hyperglycémie chronique du diabète est associée à des dommages à long terme, la dysfonction et la défaillance de divers organes, en particulier les yeux, les reins, les pieds, les nerfs, le cœur et les vaisseaux sanguins.

La grande majorité des cas de diabète se répartit en deux grandes catégories. La première catégorie, le diabète de type 1 généralement diagnostiqué chez les enfants et les jeunes adultes, est due à une carence absolue de la sécrétion d'insuline. Dans la deuxième catégorie, le diabète de type 2, la cause est une combinaison de résistance à l'action de l'insuline et une réponse de sécrétion d'insuline compensatoire insuffisante. Dans ce projet, nous n'étudierons que le diabète de type 2, qui est de loin le plus important en nombre de personnes concernées (90-95% des diabétiques). Nous mettrons également l'accent sur l'ulcère du pied pouvant survenir chez les diabétiques de type 2.

Dans le diabète de type 2, un degré d'hyperglycémie est suffisant pour provoquer des changements pathologiques et fonctionnels dans divers tissus cibles, mais sans symptômes cliniques. Il peut être présent pendant une longue période de temps avant que le diabète ne soit détecté. Le degré d'hyperglycémie dans les diabètes de type 2 peut changer au fil du temps, en fonction de l'ampleur du processus de la maladie sous-jacente.

La prévalence du diabète dans le monde augmente de façon spectaculaire et constitue un problème de santé publique grave, surtout pour ses manifestations tardives dévastatrices, qui

détermine un taux élevé de morbidité et de mortalité. En 1995, l'Organisation Mondiale de la Santé a estimé la prévalence du diabète dans le monde à 4% et le nombre de diabétiques à 135 millions. En 2009, 347 millions de personnes souffraient de cette maladie, et 500 millions sont attendues en 2030, ce qui correspond à une prévalence de 5,4%. En 2004, 3,4 millions d'individus sont morts du diabète. Le diabète est la septième cause de décès dans le monde et affecte surtout les pays pauvres.

Le pied diabétique

Les complications du pied sont parmi les complications les plus graves et coûteuses du diabète. Les pieds des personnes atteintes de diabète peuvent être affectés par la neuropathie périphérique, une maladie artérielle périphérique, une déformation du pied, une infection, un ulcère et la gangrène. L'amputation de toute ou partie du pied est généralement précédée par un ulcère du pied. En 2005, toutes les 30 secondes, un membre inférieur est amputé dans le monde à cause du diabète.

Les facteurs qui contribuent à la maladie du pied diabétique sont présents dans plus de 10 % de la population lorsqu'il est diagnostiqué avec le diabète de type 2. On estime qu'entre 15 à 25% des patients atteints de diabète finiront par développer un ulcère du pied. Les lésions du pied diabétique résultent souvent de deux ou plusieurs facteurs de risque qui se produisent ensemble. Chez la majorité des patients, la neuropathie diabétique périphérique joue un rôle central dans l'apparition de l'ulcération : jusqu'à 50 % des personnes atteintes de diabète de type 2 ont une neuropathie et des pieds à risque. La neuropathie entraîne un pied insensible et parfois déformé, souvent avec un schéma de marche anormal. Chez les personnes atteintes de neuropathie, un traumatisme mineur - causé, par exemple, par des chaussures mal ajustées, une marche pieds nus ou une blessure grave - peut provoquer un ulcère chronique. Quelle que soit la cause première, le patient continue de marcher sur le pied insensible, ce qui altère la cicatrisation ultérieure. La maladie vasculaire périphérique, généralement en conjonction avec un traumatisme mineur, peut entraîner une douleur ou un ulcère du pied purement ischémique. Cependant, chez les patients ayant à la fois une neuropathie et une ischémie, les symptômes peuvent être absents malgré l'ischémie périphérique sévère.

Toutes les personnes atteintes de diabète doivent être examinées au moins une fois par an par un médecin spécialisé pour des problèmes potentiels de pieds. Les patients avec un facteur de risque démontré devraient être examinés plus souvent - tous les 1 à 6 mois. L'absence de symptômes ne signifie pas que les pieds sont en bonne santé, le patient peut avoir une neuropathie, une maladie vasculaire périphérique, ou même un ulcère sans se plaindre. Suite à

cet examen, une classification par risque de développer un ulcère du pied est donnée par le médecin. Cette classification n'est pas la même dans tous les pays. Au Pérou, par exemple, la classification se fait selon 3 niveaux : risque faible, moyen ou élevé.

A partir de l'analyse médicale, une classification par maladie peut également être proposée par le médecin :

- Sain (pas d'ischémie ni neuropathie) ;
- Ischémie ;
- Neuropathie ;
- Mixte (ischémie + neuropathie).

Les deux approches de classification (par risque et par maladie) seront utilisées dans l'étude médicale.

Dans les premiers stades de la maladie, les signes d'ischémie possible ou neuropathie sont subtiles. Parmi tous les signes possibles, la température est une caractéristique importante dans le pied diabétique. La pratique de santé actuelle de l'évaluation de la température est la palpation manuelle de la température du pied. Cependant, l'augmentation de température est généralement trop fine pour être détectée manuellement. La cartographie de la température du pied avec un thermomètre est assez fastidieuse, et l'utilisation d'un instrument thermographique pour l'imagerie de la température de l'ensemble du pied est donc une option intéressante. La température plantaire varie chez le pied diabétique en raison de problèmes de thermorégulation liés à la neuropathie, l'ischémie ou une infection. Généralement, les variations possibles de la température plantaire sont généralement inférieures à 4 °C, mais une variation plus grande est présente chez les patients diabétiques que chez les sujets témoins. Les patients ressentent rarement la douleur à cause de la perte sensorielle neuropathique, ce qui indique qu'une température accrue peut être un signe prédictif utile d'ulcération du pied et de l'inflammation des pieds. Toutefois, afin de définir l'augmentation de température, une température de référence normalisée qui peut être utilisé pour une catégorie de risque spécifique de patients est nécessaire. La température du pied varie selon le patient et dépend de la température ambiante et du niveau d'activité. La référence la plus souvent utilisée est donc une zone correspondante sur le pied controlatéral. Les températures des zones correspondantes des pieds droit et gauche ne diffèrent généralement pas de plus de 1 °C, et une différence de température de plus de 2,2 °C est considérée comme anormale.

Le but de ce projet est d'évaluer le potentiel de la thermographie pour le diagnostic précoce de type 2 pied diabétique, à partir d'images obtenues avec une caméra infrarouge. Notre attente est de constater que la température pourrait aider dans le diagnostic précoce du pied diabétique, et peut aider à prévenir l'apparition d'un ulcère du pied. Principaux avantages de la thermographie est qu'elle est simple à utiliser, non invasif, sans contact, non irradiante et rapide. Quatre objectifs ont été définis:

- Élaborer un protocole robuste d'acquisition d'image thermographique pour le diagnostic et le suivi du pied diabétique ;
- Développer un outil logiciel pour l'analyse automatique de la température de la surface plantaire des pieds droit et gauche ;
- Déterminer le protocole de recrutement de patients pour une étude clinique transversale ;
- Mener une étude clinique transversale afin de trouver la corrélation entre les paramètres de température de la voûte plantaire avec la classification médicale pour aider au diagnostic précoce du pied diabétique et / ou à prévenir l'apparition d'un ulcère du pied.

3. Thermal Images

This chapter concerns the applications of thermal images in various areas, and especially those in medicine focusing on diabetic foot. Finally, the thermal camera that will be used for the present study will be chosen.

3.1. Technology of thermal camera

Heat transfer is described by three main modes. The first is conduction, requiring contact between the object and the sensor to enable the flow of thermal energy. The second mode of heat transfer is convection where the flow of a hot mass transfers thermal energy. The third is radiation. The latter two modes led to remote detection methods.

Thermal cameras are based on the radiation mode in the infrared spectral domain (from 1µm to 1mm). The Stefan-Boltzmann law quantifies these exchanges. The thermal power emitted by a black body is given by:

$$P = \epsilon S \sigma T^4$$

where:

- σ: is the Stefan-Boltzmann constant ($5,6703 . 10^{-8}$ W.m^{-2}.K^{-4}) ;
- ϵ: is the emissivity of a black body between 0 and 1 depending on the surface of the object;
- S: is the surface of the object;
- T: is its temperature (in Kelvin).

The Planck law describes the spectral distribution of a black body. There is a peak value which can be estimated using the Wien law: λ = 2898/T, where λ is the wavelength in μm, and T is the temperature in Kelvin. For a human skin having a temperature of 32°C, the peak value is of wavelength 9.5 μm.

Once emitted, radiations can be acquired using a thermal IR camera. Improvements in thermal imaging cameras have had a major impact, both on image quality and speed of image capture. Early single element detectors were dependent on optical mechanical scanning. Both spatial and thermal image resolutions were inversely dependent on scanning speed. The Bofors and some American imagers scanned at 1 to 4 frames per sec. AGA cameras were faster at 16 frames per sec, and used interlacing to smooth the image. Multi-element arrays were developed in the United Kingdom and were employed in cameras made by EMI and Rank. Alignment of the elements was critical, and a poorly aligned array produced characteristic banding in the image. Prof. Tom Elliott F.R.S. solved this problem when he designed and produced the first significant detector for faster high-resolution images that subsequently became known as the Signal Processing In The Element (Sprite) detector. Rank Taylor Hobson used the Sprite in the high-resolution system called Talytherm. This camera also had a high specification Infrared zoom lens, with a macro attachment. Superb images of sweat pore function, eyes with contact lenses, and skin pathology were recorded with this system.

With the end of the cold war, the greatly improved military technology was declassified and its use for medical applications was encouraged. As a result, the first focal plane array detectors came from the multi-element arrays, with increasing numbers of pixel/elements, yielding high resolution at video frame rates. Uncooled bolometer arrays have also been shown to be adequate for many medical applications. Without the need for electronic cooling systems, these cameras are almost maintenance free. The technology of the IR sensors is described in appendix A.
Next sections deal with applications of IR thermography.

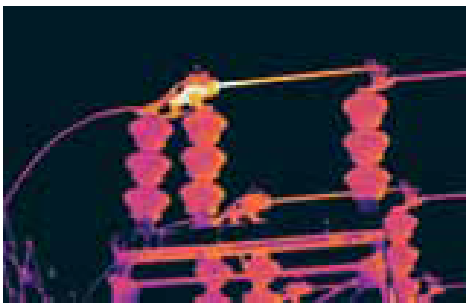# 3.2. Industrial applications of thermal images

Thermal imaging cameras for industrial applications are powerful and non-invasive tools for monitoring and diagnosing the condition of electrical and mechanical installations and components. A thermal imaging camera is useful to identify problems early, allowing them to be documented and corrected before becoming more serious and more costly to repair. A

thermal image that includes accurate temperature data provides the maintenance expert with important information about the condition of the inspected equipment. These inspections can be done with the production process in full operation and in many cases the use of a thermal imaging camera can even help to optimize the production process itself. Thermal imaging cameras are such a valuable and versatile tool with several possible applications. New and innovative ways of using this technology are being developed every day.

Electrical systems Applications

Thermal imaging cameras are commonly used for inspections of electrical systems and components in all sizes and shapes. The multitude of possible applications for thermal imaging cameras within the range of electrical systems can be divided into two categories: high voltage and low voltage installations.

Examples of failures in high-voltage installations that can be detected with thermal imaging:
- Oxidation of high voltage switches;
- Overheated connections;
- Incorrectly secured connections;
- Insulator defects.

Figure 3.1: Thermal image of high voltage connections
[Flir, 2011]

These and other issues can be spotted at an early stage with a thermal imaging camera. A thermal imaging camera will help to accurately locate the problem, determine the severity of the problem, and establish the time frame in which the equipment should be repaired.

One of the many advantages of thermal imaging is the ability to perform inspections while electrical systems are under load. Since thermal imaging is a non-contact diagnostic method, a thermographer can quickly scan a particular piece of equipment from a safe distance, leave the hazardous area, return to office and analyze the data without ever putting persons in harm's way. Normally, thermal imaging cameras for industrial applications are handheld and battery operated, they can also be used for outdoor inspections: high voltage substations, switchgear, transformers, and outdoor circuit breakers can be inspected quickly and efficiently.

Mechanical Installations

In many industries, mechanical systems serve as the backbone of operations. Thermal data collected with a thermal imaging camera can be an invaluable source of complimentary information to vibration studies in mechanical equipment monitoring. Mechanical systems will heat up if there is a misalignment at some point in the system. Conveyor belts are a good example. If a roller is worn out, it will clearly show in the thermal image so that it can be replaced. Typically, when mechanical components become worn and less efficient, the heat dissipated will increase. Consequently, the temperature of faulty equipment or systems will increase rapidly before failure. By periodically comparing readings from a thermal imaging camera with a machine's temperature signature under normal operating conditions, a multitude of different failures can be detected.

Motors can also be inspected with a thermal imaging camera. Motor failures like brush contact-wear and armature shorts typically produce excess heat prior to failure but remain undetected with vibration analysis, since it often causes little to no extra vibration. Thermal imaging gives a full overview and allows to compare the temperature of different motors. Other mechanical systems monitored with thermal imaging cameras include couplings, gearboxes, bearings, pumps, compressors, belts, blowers and conveyor systems (Figure 3.2).

• Lubrication issues;
• Misalignments;
• Overheated motors;
• Suspect rollers;
• Overloaded pumps;
• Overheated motor axles;
• Hot bearings.

Figure 3.2: Thermal image of suspected roller [Flir, 2011]

These and other issues can be spotted at an early stage with a thermal imaging camera. This will help to prevent costly damages and to ensure the continuity of production.

Refractory and petrochemical installations

A wide variety of industries rely on furnaces and boilers for manufacturing processes, but the refractory linings for furnaces, boilers, kilns, incinerators, crackers and reactors are prone to degeneration and loss of performance. With a thermal imaging camera, damaged refractory

material and the corresponding heat loss can be easily located, as the heat transmission will show up clearly on a thermal image. Thermal imaging cameras are widely used in the petrochemical sector (see Figure 3.3). They provide rapid, accurate diagnosis for furnace maintenance, refractory loss management and condenser fin diagnosis. Heat exchangers can be checked to detect blocked pipes. But furnace and boiler equipment is also prone to failures from a variety of other mechanisms. These include coking that plugs the inside of tubes and impedes product flow, slag build-up on the outside of tubes, under and overheating, flame impingement on tubes due to burner misalignment, and product leaks that ignite and cause serious damage to the equipment. To ensure refractory quality of boiler and furnace installations, it is not enough to just perform inspections from the outside. The refractory on the inside of the boiler or furnace has to be inspected as well. With conventional methods, it is necessary to shut down the installation to be able to inspect the inside. This is extremely costly due to a loss of production during downtime.

Figure 3.3: Thermal image of refractory insulation inspection on a petrochemical reactor [Flir, 2011]

Other industrial applications include:

- Finding hot spots in public buildings or private houses;
- Finding welding robots;
- Inspection of aeronautical material;
- Mould inspection;
- Checking temperature distribution in asphalt pavements;
- Inspections in paper mills, …

3.3. Applications of thermal image in medicine

Thermography is a non-invasive, non-contact skin surface temperature screening method that is economic, quick and does not inflict any pain on the patient. It is a relatively straight forward imaging approach that detects the variation of temperature on the human skin surface.

Thermography is widely used in the medical arena and we focus on some promising applications.

3.3.1. Preventive breast cancer screening

From the last 15 years of complying with the strict standardized thermogram interpretation protocols by proper infrared trained personnel as documented in literature, breast thermography has achieved an average sensitivity and specificity of 90%. An abnormal thermogram is reported as the significant biological risk marker for the existence of or continues development of breast tumor [Ng, 2008]. This review paper further discusses the performance and environmental requirements in characterizing thermography as being used for breast tumor screening under strict indoor controlled environmental conditions. The essential elements on performance requirements include display temperature color scale, display temperature resolution, emissivity setting, screening temperature range, workable target plane, response time and selection of critical parameters such as uniformity, minimum detectable temperature difference, detector pixels and drift between auto-adjustment. This paper however does not preclude users from potential errors and misinterpretations of the data derived from thermal imagers.

The earliest breast thermogram was reported by [Lawson, 1963]. He observed that the venous blood draining the cancer site is often warmer than its arterial supply. However, these measurements have never been confirmed by others and the findings might thus have been questionable. Thermograms alone however will not be sufficient for the medical practitioner to make a diagnosis. Analytical tools such as bio-statistical methods and artificial neural network are recommended to be incorporated to analyze the thermogram objectively [Ng, 2004]. Notice that these approaches may improve the interpretation of thermal images which may lead to a higher diagnostic accuracy of infrared thermography, but these methods for analysis are not more objective than any other highly accurate and precise measurement. With the rising use of thermal imaging, there is a need to have regulations and standards to provide accurate and consistent results. The standards are mainly based on the physics of radiation and thermoregulation of the body.

[Keyserlingk et al.,1998] observed that the tumor diameter missed in thermogram was 12.8 mm and that in a mammogram was 16.6 mm. They conducted a study using a retrospective case-control design to investigate the potential adjuvant benefit that could be gained from infrared imaging in a multi-modality diagnostic setting. They reported that the sensitivity for the detection of ductal carcinoma by clinical examination alone was 61%, by mammography alone was 66%, and by infrared (IR) imaging alone was 83%. When suspicious and equivocal mammograms were combined the sensitivity increased to 85%. A sensitivity of 95% was

obtained when suspicious and equivocal mammograms were combined with abnormal IR images. However, when clinical examination, mammography, and IR images were combined, a sensitivity of 98% was achieved. Both IR imaging and mammography technologies are of complementary nature. Neither used alone is sufficient, but when combined, each may counteract the deficiencies of the other. Thermography may have the potential to detect breast cancer 10 years earlier [Gautherie, 1983] than the traditionally golden method — mammography. However, due to inconsistencies in diagnosis from breast thermograms, it has not been commonly used and is not regarded as a reliable adjunct tool to mammography currently.

The main components recommended to characterize thermal imaging as a potential complimentary tool for breast cancer detection include:

- Thermal radiation theory,
- Preparation of patient,
- Examination environment,
- Standardization of thermal imager system,
- Image capture protocol,
- Image analysis protocol, and
- Reporting, archiving and storing.

Although IR systems have many advantages for temperature screening, other than its cost, there are however many variables that can affect its accuracy [Houdas, 1982] [Ng, 2005]. Ideally, the thermal imager should be operated in a stable indoor environment with stability of the operating ambient temperature within ±1 °C, and facilities to control all ambient conditions such as temperature, humidity and additional infrared sources.
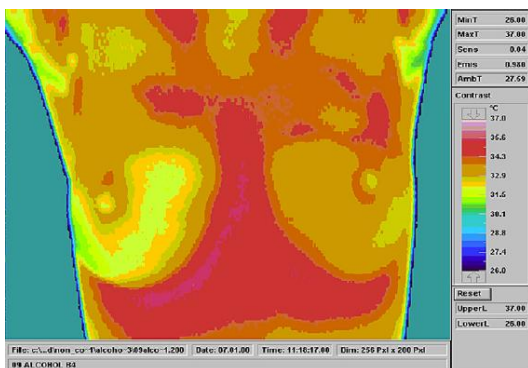
Figure 3.4: Typical thermogram of an asymptomatic volunteer aged of 35 [Ng, 2009]
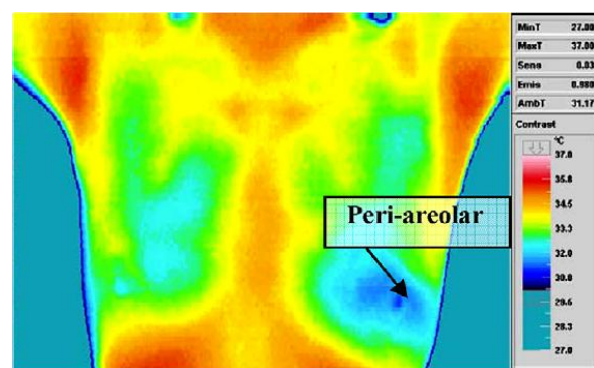
Figure 3.5: Asymmetric thermogram of a 52 year old woman with left breast abnormality [Ng, 2009]

Figures 3.4 and 3.5 (Ng, 2009] illustrate examples of a typical thermogram of an asymptomatic volunteer (aged of 35) and a typical asymmetric thermogram of a 52 year old woman with left breast abnormality. Based on mammographic examinations in 1000 Singapore women on the eve of the breast cancer awareness month (Oct. 1998, [Wang, 2003]), the average size of a cancerous lump [Ng et al, 2001] was 1.415 cm in spheroid shape when detected in the clinic for the first time. From the breast thermograms, temperature data are extracted from them. The thermograms consist of many colored pixels, each representing a temperature. From the thermograms, it is possible for an experienced medical practitioner to diagnose abnormalities such as a cyst. After every pixel's temperature is compiled, bio-statistical technique can be used to treat them, such as determining the mean, median and modal temperature of the breast region.

In summary, thermal imagers offer an excellent means of making a qualitative determination of surface temperature, but there are many difficulties in obtaining an absolute measurement. Some researchers concluded that the thermogram provides a reflection of functional tumor induced by angiogenesis and metabolic activity rather than structurally based parameters (i.e. tumor size, architectural distortion, microcalcifications, [Keyserlingk et al, 2006]). With a direct reflection of the biological activity in the breast, IR imaging has been recommended as a significant biological risk marker for cancer [Keith et al, 2001].

3.3.2. Extremities perfusion dynamic evaluation by thermography analyses

Skin is an organ which cools us as well as keeps us warm by letting heat out or keeping it in by controlling/regulating the amount of circulation, or blood flow, in the skin. This automatic regulation is done without conscious thought and is controlled by the autonomic nervous system via the sympathetic nerves. The whole biochemical process is called the body thermoregulation [Pasco, 2006]. Today many people have cold hands, cold feet, sharp pain in the legs, peripheral arterial disease. These symptoms may be early warning signs of more serious blood circulation problems. To prevent progression of these symptoms we developed a sophisticated early detection possibility method based on dynamic thermography technology. Measurement of the skin surface temperature is a crucial component of energy transfer. Thermography is a non-invasive diagnostic technique based on digital imaging which is able to detect pathologies that are difficult to detect using other methods and at a much earlier stage of their evolution. The physiological and pathophysiological basis of thermography is the dissipation of body heat through the skin which is detected as infrared radiation and which depends on the flow and volume of the subcutaneous blood circulation dynamics.

In cases where diseases are associated with neurogenic inflammation, the liberation of nitric oxide produces intense vasodilatation and consequently a significant increase in the emission of infrared radiation energy. These inflammatory diseases may be the result of trauma, rheumatism or infection or even cancer. Thermal imaging through the thermal map distribution is able to pinpoint the location of this inflammation. The temperature gradient is often less than 1°C, which means that leaf temperature should be measured to within 0.07°C (at 30°C) temperature resolution and high spatial resolution (min. detectable size is 0,64 mm²).

Extremities perfusion dynamic evaluation is possible with advanced high sensitive and sophisticated dynamic thermography methods. Objectives of the research is to provide a dynamic thermographic analytical (DTA) method which allows to produce images which are affected to a limited extent by surface blood circulation and allows to obtain a series of images from which it is possible to clearly detect the situation of functional blood circulation in various area [Skala et al., 2010].
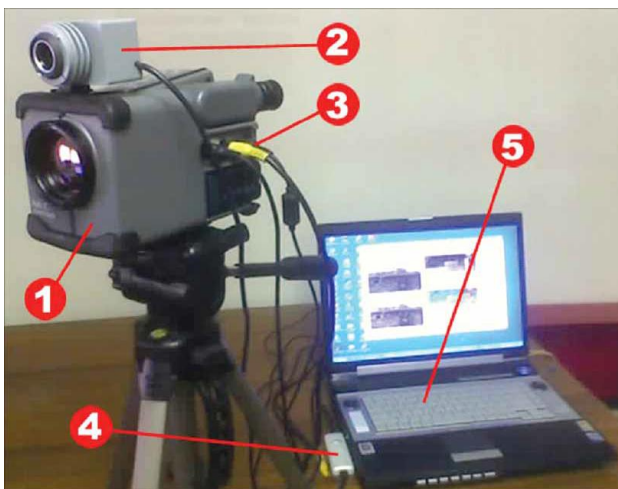
Figure 3.6: Components of the ThermoWEB system [Skala et al., 2010].

The hardware component of the ThermoWEB measuring system (Figure 3.6) includes the thermovision camera NEC Thermotracer TH7102WL (1), a video CCD color camera (640x480 pixels) (2), set in an appropriately shaped housing (IP54), with a mechanical adapter for assembly onto the housing of the IR camera, and a circuit for choosing and accepting video signals (4) from the camera to the computer (USB2) (5).

The DTA method includes temperature measurement procedure, which can be performed on one picture only (single frame-mode freeze) or it can continually monitor the time dependence of changes in temperature intensity of a point or surface by taking pictures with a maximal frequency of 60 Hz. The continued time-tracking of temperature intensity makes it possible to determine the frequency change of a single thermal surface inside the picture. The resulting thermal data can be rendered as a series of color images that can be used to differentiate normal and abnormal changes in temperature, which results in the possibility of recognizing snap action (influence) of the vascular circulation stimulator (Microstim KLM 500).
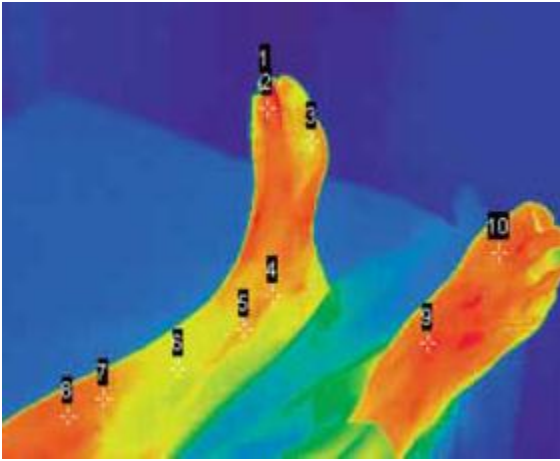
Figure 3.7: Thermal imaging of patient's legs at various times with distribution [Skala et al., 2010]

Thermographic research of blood circulation gives us closer look in the circulation itself (Figure 3.7). Thermographic probe that follows circulation stimulation with ultrasound gives a better look in dynamic possibilities of peripheral circulation, what is important in vascular medicine and vascular surgery. The method above is new in a way it allows dynamic follow-up of blood circulation after treating foot with ultrasound and vibration. Dynamic thermographs are important to determine potential capacity of capillary pool in patients with peripheral vascular insufficiency. In cases like that, it is difficult to evaluate functional status of a limb, and thermographs are a method that gives us this possibility. That fact can help surgeon with reversibility evaluation of ischemic tissue in differential cases, it can help in predicting of revascularization success, in making decision of amputation and the level of amputation. Also it gives us insight in functionality of reperfusion procedure after revascularization.

3.3.3. Other Applications of thermography in medicine

Rheumatoid arthritis is characterized by recurring inflammatory processes of the joints, accompanied by hyperthermia of the skin surfaces covering the joints. Infrared thermography provides objective, quantifiable, reproducible measures of the intensity and extent of joint involvement [Sapalding et al., 2008] [Frize et al., 2011]. The therapeutic efficacy of different treatment options on reducing the intensity of an inflammatory process can be objectively and quantitatively assessed and compared to each other by infrared imaging. This provides an alternative to the currently used semi-quantitative scoring schemes.

Raynaud's disease is characterized by sudden, intermittent painful vasospasm of the finger's digital arteries, provoked by cold or emotional stress. By infrared imaging, the severity of the disease can be quantified and consecutive attacks can be compared to each other [Fonseca et al., 2009] [Anderson et al., 2007]. Due to the difference in the underlying disease processes, the primary and secondary forms of Raynaud's syndrome can be differentiated by infrared imaging as well, which provides valuable information for further diagnostic procedures and individualized management of the disease and also has prognostic value.

Osteoarthritis of the knee: the knee joint with its delicate, complex structure is exposed to continuous heavy strain; the ensuing osteoarthritis is the degenerative disease of the tissues of the knee joint, accompanied by an inflammatory process of varying degree. In the population over 45 years, the average lifetime risk of at least one onset of clinically verified osteoarthritis, accompanied by painful symptoms and transient arthritis attributable activity limitations (AAAL) is 40–45% [Murphy et al., 2008]. Morphological changes observed by imaging methods can be detected only after a long period of time (usually after years) from the onset of signs and symptoms of the disease, even when sensitive imaging methods are used (ultrasound, MRI, scintigraphy) [Keen et al., 2011]. For these reasons, the assessment of therapeutical efficiency and the decision regarding the continuation of a certain therapy or its replacement with an alternative therapy cannot be based on the results of the traditional imaging modalities during the early, modifiable course of the disease. The patella physiologically represents a cool spot with a characteristic shape on infrared thermography, because its thick bone plate prevents the dissipation of the heat produced by the knee joint through the patella, and so forth heat is dissipated around the patellar margin, that can be detected by the presence of a slightly warmer band surrounding the patella. In case of inflammatory processes of the knee, the normally cool spot representing the patella with the surrounding slightly warmer band becomes distorted or disappears completely, and the temperature of the skin covering the inflamed knee tissues rises. Even in advanced osteoarthritis, detectable on X-ray, the increased temperature of the skin covering the patella correlates with the severity of the radiographic changes [Denoble et al., 2010]. Quantitative assessment of pain-related thermal dysfunction by infrared thermal imaging is utilized in other body parts as well.

Plastic and reconstructive surgery: in plastic and reconstructive surgery, infrared thermography is gaining acceptance in many ways. It is an excellent diagnostic tool to identify dominant perforator vessels before free flap surgery, which helps in preoperative planning. It is an outstanding method to monitor the perfusion of the free flap after connecting its vessels (artery and vein) to the site of reconstruction intraoperatively. In the postoperative period, it is a sensitive, valuable method to assess the free flap in difficulty, and to decide whether the clinical symptoms are related to problems with flap perfusion or are due to other causes (infection, etc.) [De Weed et al., 2006].

Analysis of cortical cerebral perfusion by the "cold saline" technique: minute changes (<0,01K) in cerebral cortical surface temperature can be detected by infrared imaging. It has led to the proof of concept study of measuring the cortical cerebral perfusion by the cold saline technique. A small amount (10 mL) of ice cold saline was administered as a bolus into a central vein, and subsequent changes in cerebral cortical temperature have been recorded by infrared video thermography and analyzed by principal component analysis (PCA) in patients who were operated on for their cerebral pathologies (ischemic stroke, brain tumor, etc.). It has

been shown that the method is able to differentiate between cortical regions with good or poor perfusion [Steiner et al., 2011].

Infrared video thermography for the frequency domain assessment of the arteriolar microcirculation: since 2008, a number of Proof of Concept (PoC) works have been published on the time and frequency domain analysis of infrared image streams, and a new, potentially very important application of infrared video thermography has emerged. Infrared thermography and image analysis have been shown to be suitable methods for the power spectral density (PSD) analysis of arteriolar microcirculation in real time, when tested against the current golden standard Laser Doppler Flowmetry (LDF) and Laser Speckle Imaging (LSI) methods [Gorbach et al., 2008] [Gorbach et al., 2009]. These PoC studies have shown that infrared imaging-derived temperature fluctuations (thermal oscillations) provide temperature profiles of the skin surface over time that can be subjected to spectral (frequency) analysis.

The 6 characteristic frequency bands in the complex waveform of the arteriolar microcirculation are:

- **Cardiogenic** signal component in the 0,6–2 Hz band;
- **Respiratory** component in the 0,145–0,59 Hz band;
- **Intrinsic vessel wall** (arteriolar wall) motion in the 0,052–0,144 Hz band originating from the synchronized motion of the smooth muscle cells induced by their own local pacemakers in the vessel wall;
- **Sympathetic nervous system** generated vessel wall motion in the 0,021–0,051 Hz band;
- **Slow vessel wall motion** in the 0,0095–0,020 Hz frequency band, generated by the endothelial cells primarily by their nitric oxide production affecting vessel wall's smooth muscle cells by paracrine action;
- **Very slow oscillation** in the 0,005–0,0094 Hz frequency band, generated by the endothelial production of non-nitric oxide compounds.

The gold standard LDF results and the results gained by frequency domain analysis of the infrared thermography image streams provided identical results. The advantage of infrared thermography based frequency domain analysis is apparent: the size of the area that can be analyzed in real-time by infrared thermography is 1.000x – 10.000x higher than the area assessed by LDF. Gorbach et al. have demonstrated in animal experiments that infrared images obtained during renal ischemia-reperfusion immediately showed which segments of the kidney were ischemic. Dominant frequency (DF) of the tissue temperature fluctuations were determined by FFT analysis. The authors demonstrated that DF at 0.008 Hz corresponds to blood flow oscillations which were diminished after 25 min. of warm ischemia and were recovered with reperfusion in a time-dependent manner. Comparative microcirculation

assessment was performed in the hand by the same group with LDF and infrared imaging, with excellent agreement between the two methods.

3.4. Research work using thermal images in diabetic foot

Temperature is an important characteristic in diabetic foot. In the recent past years, traditional infrared camera has made tremendous progress. Their price has been dramatically reduced while the technical progress strongly increased. Such technologies are serious candidates for detecting thermal changes in diabetic foot disorders. All these reasons make that the interest of measuring the temperature of the foot using thermal images becomes more and more an active research topic as explained in the following.

3.4.1. Detection and evaluation of plantar temperature by IR thermography

[Nagase et al., 2010] studied thermographic images of the plantar skin temperature of the control and the DM groups (Diabetic group). These images were obtained as reported previously [Nishide et al., 2009]. The subjects were guided to maintain supine position without shoes or socks for 15 min. in a room controlled at a temperature of 26 ± 0.5 °C before measurement. After equilibration, thermographic images were taken using Thermotracer (TH5108ME, NEC Avio Infrared Technology Co., Ltd. Tokyo, Japan) by nurses specialized in diabetic foot care, in a consistent manner (Fig. 3.8). Each plantar thermographic image was allocated to the 20 different categories, as described above in 2.2.3, by a plastic surgeon with experience in diabetic foot care. To avoid observation bias, this allocation was further confirmed by the two trained nurses. When the allocations differed among the investigators, the images were reviewed again by all of the three investigators to make a final decision. If the images did not correspond to any of the 20 categories, they

Figure 3.8: Bilateral butterfly pattern of the plantar thermography in a control subject reported by [Chan et al, 1991]

were designated as 'atypical'. Thermography of the dorsal feet and digital photographs of the skin surfaces were also obtained from some cases with 'atypical' thermographic patterns.

The ankle brachial index (ABI) and toe brachial index (TBI) were measured from the control and DM groups using form pulse-wave velocity/ankle brachial index (PWV/ABI) BP-203RPEII (Omron Colin Co., Ltd., Tokyo, Japan). ABI and TBI are clinical gold standards for estimating blood flow of the lower leg and the toe, respectively. In this study, ABI was significantly higher in the DM group than in the control group. This finding can be interpreted by the reasoning that the higher ABI in the DM group was not due to good blood supply, but due to an artefact because of stiffness of the atherosclerotic posterior tibial artery. On the other hand, TBI was significantly lower in the DM group than in the control group, possibly reflecting decreased blood supply in the distal foot in the DM group. However, more precise relationship between thermographic pattern and circulation at the angiosome level should be investigated in future by computed tomography (CT) or magnetic resonance (MR) angiography or more meticulous examination using a Doppler probe described by [Attinger et al., 2006].

3.4.2. Relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet

Risk identification is fundamental in the preventive healthcare management of the diabetic patients having potential foot problems. The autonomic neuropathy in the lower limbs of diabetic patients leads to vasomotor disturbance, reduced sweating and abnormal skin conditions including anhydrosis, fissures and blisters [Watkins, 2003]. Peripheral autonomic dysfunction was found to be associated with the development of foot lesions in diabetic subjects. Traditional autonomic tests with evaluation mainly on cardiovascular reflex yield an assessment more of the central autonomic function. Clinical examinations (e.g. monofilament and tuning fork) and nerve conduction studies do not adequately investigate the degree of peripheral autonomic involvement [Kimura, 2001]. The sympathetic skin responses (SSR) involving multiple levels of the nervous system can be used to assess the sudomotor function of the extremity by reflecting the integrity of unmyelinated sympathetic fibers. It was reported that most diabetic patients with generalized autonomic symptoms revealed absent sympathetic skin response. However, the decreased sudomotor activity has not yet been investigated using the SSR assessment in diabetic patients at risk of foot complications.

Skin temperature has been used to detect acute tissue damage in neuropathic joint and ulcer [Boyko, 2001]. Thermal images can be an adjuvant in the diagnosis of these major foot lesions. Nevertheless, little is known of the range of abnormal thermoregulation in the diabetic patients with minor skin lesions. The skin temperature was not well studied in

diabetic feet with varying degrees of polyneuropathy. It might be of interest to determine whether thermal asymmetry in neuropathic feet is related to their clinical or electrophysiological abnormalities. The purpose is to characterize the distribution of the diabetic foot skin temperature and seek correlation of the mean skin temperature with autonomic dysfunction as detected by sympathetic skin response as well as cardiovascular reflex tests. The correlation of the mean skin temperature with peripheral somatic neuropathy by using nerve conduction studies and clinical examinations should also be studied.

[Sun et al., 2006] reported a study about the relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet. In this study, subjects were recruited from the members of a diabetes association, representing a diabetic population with fairly good medical conditions. Patients with history of foot ulcer, overt neurological symptoms or peripheral vascular diseases (ankle brachial pressure index < 0.9) were excluded from this study. Informed consents were obtained from all the participants. There were 69 type 2 diabetic patients and 25 nondiabetic control subjects chosen for this study. The diabetic patients were classified depending on the presence of minor skin lesions and the result of the sympathetic skin response test in both feet. There were 29 diabetic patients who showed presence of the sympathetic skin responses SSR and were classified as the SSR+ group. Among the remaining 40 diabetic patients with absent SSR, 18 patients having preulcerative foot lesions such as dry and fissured skin were considered as the at-risk group, and other 22 patients did not have the minor skin lesions (SSR_ group). Note that the SSR was found present over both feet in all the control subjects as expected. The criterion used to screen for minor skin lesions were based on the Seattle Wound Classification System graded 1.2–1.3, i.e., cracked or fissured skin involving only epidermis or dermis layers [Litzelman, 1997].

Skin temperatures of both feet were assessed using medical thermal imaging radiometer system (Spectrum 9000 MB; Biovision Technologies, Inc., Taipei, Taiwan). The operator who measured and stored the thermal data was blinded as to either the grouping or the condition of the feet of all the subjects. All measurements were performed in the morning to eliminate the influence of diurnal temperature variation on the subjects. All subjects were asked to remain in a seated position with bare feet for 15–20 min. to achieve equilibration with the constant ambient temperature (21 ± 1 °C). A cool test environment was required for reliable data acquisition during the thermographic measurement as reported by prior study [Sun et al., 2006]. The plantar thermal image was divided into six regions of interest as shown in Figure 3.9, and the mean foot temperature was calculated from these six regions. The group temperature average was obtained from the average value of both feet of the subject. The forehead temperature was also measured as a reference in order to conduct a data process of temperature normalization by the forehead temperature as given below.
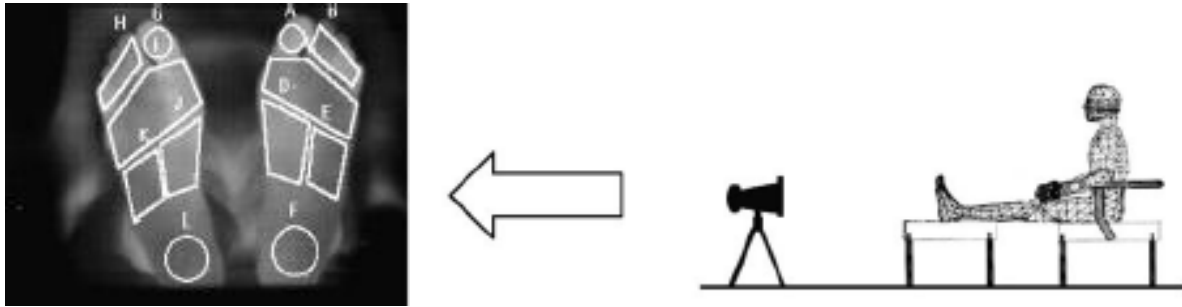
Figure 3.9: Experimental set-up and graphic representation of designated areas in both feet: A and G, hallux; B and H, lesser toes; C and I, forefoot; D and J, arch; E and K, lateral sole; F and L, heel. [Sun et al., 2006]

The normalized temperature was calculated as: $TN = |\Delta T°| / TR$ where TN is the normalized temperature (no unit), $|\Delta T°| = |TR - TMF|$ the temperature difference (°C), TR the corresponding forehead temperature (°C) and TMF is the mean foot temperature (°C). This temperature normalization was adopted in this study for its reported good reliability.

All diabetic patients underwent a quantitative neurological examination, followed by a set of nerve conduction studies to evaluate peripheral somatic nerve function. The 128 Hz tuning fork and Semmes–Weinstein monofilament were applied to the dorsum of the great toe, and the patients were asked to respond if they felt the vibration or light touch. The sensation, muscle strength and tendon reflex was scored separately according to the described criteria [Feldman, 1994]. The sural, peroneal motor, median sensory and motor, and ulnar sensory nerves were evaluated. The severity of somatic neuropathy was graded according to the Michigan Diabetic Neuropathy Score. Each patient was given a composite score and graded based on the sum of scores on the clinical examination and the number of abnormal nerve conductions. Diabetic patients with neuropathy score > 6 points were considered clinically abnormal, and patients having two or more abnormal conduction studies were considered electrophysiologically abnormal.

The measurement of plantar skin temperature using infrared can discern small thermal difference beyond the palpable limit, particularly for the patients without gross inflammatory symptoms as in our experiment. Sympathetic dysfunction in the lower limbs leads to reduced sweating and dry skin, which is prone to crack and fissure. These dermatological conditions are highly related to thermoregulatory sweating abnormalities [Springett, 2002]. The diabetic patients in this study were categorized based on the degree of peripheral sudomotor dysfunctions. The concordance of results of the patients' grouping and the skin temperature difference implies that small fiber neuropathy plays a preliminary role in the development of microcirculatory disturbance. The at-risk patients all showed absence of sympathetic skin response in both feet. The decreased sudomotor activity and concomitant thermoregulatory disturbance should be an early sign of sympathetic damage in diabetic feet [Hoeldtke, 2001].

Note that the peripheral small fiber neuropathy could not be accurately evaluated by the clinical and autonomic tests mentioned previously. The temperature and electrophysiological assessment conducted in this study proved to be useful for healthcare providers to identify the patients with sympathetic dysfunction in early stage to warrant their feet care.

In conclusion, the thermoregulatory disturbance and sweating dysfunction should be a sign of early sympathetic damage in diabetic feet. Assessing skin conditions and sudomotor activities shall help healthcare providers to identify the patients with small fiber neuropathy in early stage more accurately, in order to alert them of their feet conditions [Sun et al., 2006].

Skin Temperature Monitoring Reduces the Risk for Diabetic Foot

This study talks about "Skin Temperature Monitoring Reduces the Risk for Diabetic Foot Ulceration in High-risk Patients" developed by [Armstrong et al., 2007]. Self-evaluation of temperature seems to offer a mechanism to identify an early sign of injury, when there is still time to avert a wound. The results of this study suggest that a simple, inexpensive temperature device can be used effectively by high-risk patients to reduce foot ulceration. The purpose of this study is to evaluate the effectiveness of home temperature monitoring to reduce the incidence of foot ulcers in high-risk patients with diabetes.

The characteristics of this physician-blinded study were: 18-month randomized controlled trial, 225 subjects with diabetes at high-risk for ulceration; patients had either a history of previous diabetic foot ulceration or amputation (Standard Therapy Group) or were with sensory neuropathy and loss of protective sensation with structural foot deformities (Dermal Thermometry Group). They were assigned to standard therapy (Standard Therapy Group) or dermal thermometry (Dermal Thermometry Group) groups. Both groups received therapeutic footwear, diabetic foot education, regular foot care, and performed a structured foot inspection daily. Dermal Thermometry Group subjects used an infrared skin thermometer to measure temperatures on 6 foot sites twice daily. Temperature differences >4°F between left and right corresponding sites triggered patients to contact the study nurse and reduce activity until temperatures normalized.

A total of 8.4% (n=19) of all subjects ulcerated over the 18-month follow-up period. In the Standard Therapy Group, 12.2% (n=14) of patients ulcerated compared with 4.7% (n=5) of those in the Dermal Thermometry Group (Odds Ratio 3.0, 95% confidence interval (CI), 1.0 to 8.5, P=0.038). Proportional hazards regression analysis suggested that thermometry intervention was associated with a significantly longer time to ulceration (P=0.04), adjusted for elevated foot ulcer classification (International Working Group Risk Factor 3), age, and minority status. Patients that ulcerated had a temperature difference that was 4.8 times greater at the site of ulceration in the week before ulceration than did a random 7 consecutive-day

sample of 50 other subjects that did not ulcerate (3.50±1.0 vs 0.74±0.05, P=0.001). Conclusions of this study state that high temperature gradients between feet may predict the onset of neuropathic ulceration and self-monitoring may reduce the risk of ulceration. Detecting this increased temperature and providing adequate therapy can reduce the incidence of foot ulcer by 3. This result is of major importance.

Monitoring Neuropathic Ulcer Healing with Infrared Dermal Thermometry

The purpose of another study [Armstrong et al., 1996] was to prospectively evaluate skin temperatures at the site of neuropathic ulceration before, during, and after wound healing using the contralateral extremity as a physiologic control and to evaluate variables that may influence skin temperature gradients. They studied 17 male and 8 female diabetics with mean age and duration of diabetes of 52.4 ± 11.6 years and 13.8 ± 7.8 years with grade I (Meggitt-Wagner) plantar ulcers. All patients received weekly cast changes with wound and skin temperature assessments. After healing, all patients were fitted with prescription shoe gear. Temperatures on the ulcerated foot were higher than those on the contralateral foot on initial presentation (91.1 vs. 84.2°F, t = 8.9, P < 0.0001, 95% CI 5.3 to 8.5), but the same following healing. Patients with vibration perception thresholds greater than 45 V had wider skin temperature gradients than those with lesser degrees of sensory neuropathy (8.8 ± 4.1 vs. 4.9 ± 2.5°F, P=0.007). Additionally, subjects with toe brachial indices below 0.60 had greater skin temperature gradients at the site of ulceration than those with higher indices (9.4 ± 4.0 vs, 5.8 ± 3.4°F, P=0.01). There was not a significant difference in initial skin temperature gradients by duration of wound prior to treatment, duration of wound healing, sex, maximum plantar pressure, or hemoglobin A1C level.

The results of this study indicate that there are significant differences in skin temperatures in patients with ulcerations compared with the temperature of their contralateral extremity at initiation of therapy. The difference in temperature appears to decrease as the surface area of the wound decreases. Additionally, patients with very high degrees of neuropathy or reduced peripheral vascular perfusion appear to have larger skin temperature gradients than their counterparts with lesser degrees of peripheral neuropathy or greater peripheral vascular perfusion. Clearly, however, the association between vascular status and skin temperature gradient mandates further investigation. After a neuropathic ulcer heals, 20% to 58% of patients develop another ulcer within a year.

Plantar Thermographic Patterns

Variations of plantar thermographic patterns in normal controls and non-ulcer diabetic patients were studied by [Nagase et al., 2011]. Thermometry of the plantar skin temperature has been one of the important parameters for assessing ulceration risks in diabetic patients. Recent progress of infrared thermographic technology allows us to obtain imaging of temperature distribution of the whole plantar skin. However, it has not been fully elucidated to what extent the individual variation of the plantar thermographic patterns shows different trends between normal controls and diabetics. In this study, they made a novel framework of conceptual classification with 20 different categories of plantar thermographic patterns according to the foot angiosome concept, a composite unit of tissues supplied by a source artery. The thermographic images from 32 normal volunteers and 129 non-ulcer diabetic patients, recruited from Diabetes Foot Outpatient Clinic of the University of Tokyo Hospital, were allocated to the above-mentioned framework categories.

This classification (Figure 2.5) considers four plantar angiosomes according to [Attinger et al. 2006]:

- MPA: medial plantar artery;
- LPA: lateral plantar artery;
- MCA: medial calcaneal artery; and
- LCA: lateral calcaneal artery.

Note that the MPA and the LPA angiosomes are overlapped in the hallux. Orange colour indicates higher temperature, and blue colour indicates lower temperature.

To build up the classification framework, they separated the whole plantar area into the distal area and the heel. They distinguished five different patterns in the distal area. The most typical 'bilateral butterfly pattern' was designated as type I. The other four patterns were defined according to the viabilities of the MPA and LPA angiosomes:

- Type I: corresponds to the 'bilateral butterfly pattern'.
- Type 2: represents the condition when both the MPA and LPA angiosomes are intact.
- Type III: represents the condition when the MPA is occluded and the LPA angiosome is intact (the MPA angiosome is nourished by choke vessels from the adjacent angiosomes, and, thus, possibly shows lower temperature).
- Type IV: represents the situation when the LPA is occluded and the MPA angiosome is intact.
- Type V: represents the condition when both the MPA and LPA are occluded and both angiosomes are nourished by choke vessels.

They similarly distinguished four different patterns in the heel area:

- Type a: represents the condition when both the MCA and LCA angiosomes are intact.
- Type b: represents the condition when the MCA is occluded.
- Type c: represents the condition when LCA is occluded.
- Type d: represents the condition when both the MCA and LCA are occluded.

They finally crossed the five distal patterns and the four heel patterns, just like the vertical and horizontal axes of a two-dimensional space, obtaining the conceptual classification with the 20 different categories from Ia to Vd (Figure. 3.10).

In the normal group, thermographic patterns of more than 65% of feet were allocated to the two typical categories, including the 'butterfly pattern' among the 20 categories, whereas 225 feet (87.2%) of the diabetic groups were variously allocated to 18 out of the 20 categories. This is the first study which describes detailed plantar thermographic patterns, showing wider variations in the diabetic patients than in the normal subjects. Thermography will be one of the screening options to assess circulatory status in both daily foot care and surgical intervention. If it is possible to identify that blood supply of a particular angiosome is compromised by thermography in DM patients, physicians can pay more attention to prevent diabetic ulcer formation in this part in the clinical practice of foot care. Observation of the thermographic pattern according to this classification may give an important clue as a screening tool for searching for the foot angiosomes with damaged source arteries, and, thereby, avoiding such kinds of unfavorable surgical outcomes.
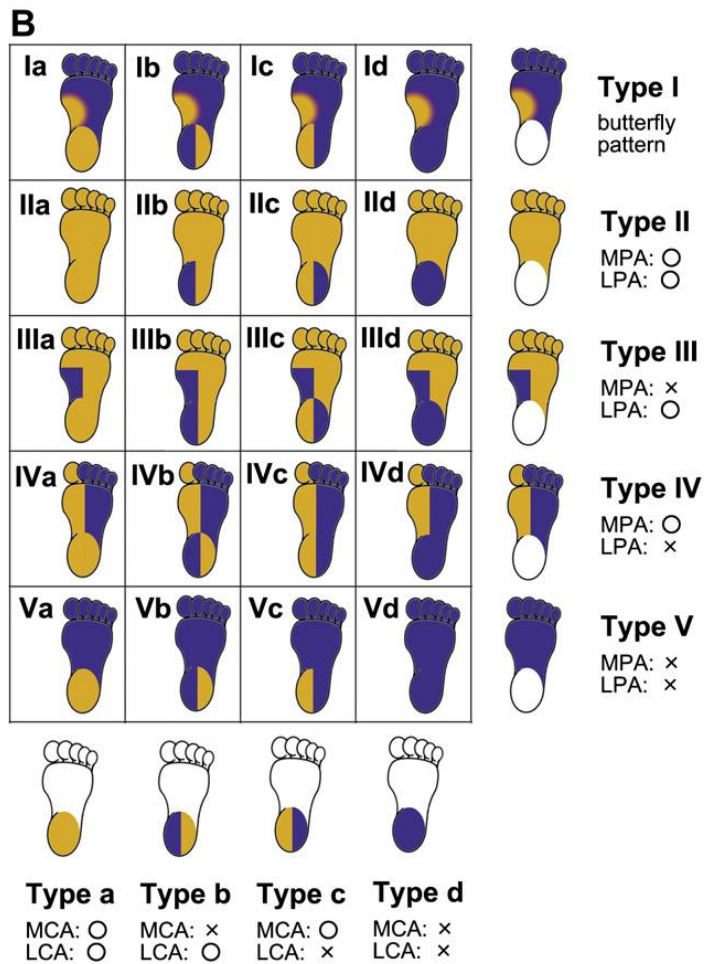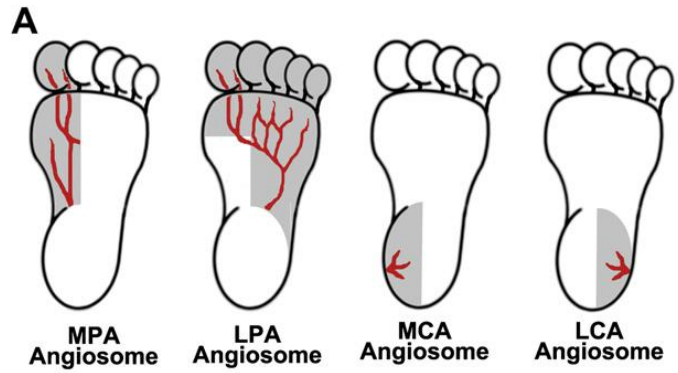
Figure 3.10: Thermographic classification of plantar based in angiosomes. A: Four plantar angiosomes. B: Classification of the plantar thermography. Source: Nagase et al., 2011

Thermography in the assessment of diabetic foot

IR thermography is a real-time temperature measurement technique used to produce a colored visualization of thermal energy emitted by the measured site at a temperature above absolute zero. [Jones et al., 2002] have provided an excellent review on IR technology along with related image-processing considerations. Traditionally, a 2-dimensional image representing 3-dimensional thermal distribution is acquired using standard image acquisition hardware. Each pixel in the image depicts the radiance falling on the focal plane array/microbolometer–type detector used in an IR camera.

Technological advances in IR cameras in speed and spatial resolution now make it possible to quantitatively assess thermal patterns. It is recommended that IR imaging equipment must be regularly calibrated, and characteristic parameters be determined using simple tests such as spatial resolution, stability of imaging protocol and quantitative techniques in medical thermography have been well described. [Jones et al., 2005] identified a common need to establish a reference database of normal thermograms from all major areas of the human body, from which the abnormal findings can be reliably assessed. The reference database is a multicenter effort to standardize IR imaging for reproducible and clinically relevant thermal measurements.

IR thermography is a noninvasive and high-resolution technique used to measure physiological changes complementing standard radiographic investigations [Jones et al., 2002]. [Wang et al., 2004] used IR thermography in a small patient group with vascular or neurological complications and emphasized the need for establishing normal variations of skin temperature before attempting to quantify abnormal criteria. The technique has been used to assess both anatomical and functional changes.

Langer and other researchers used IR thermography to study vascular complications and foot ulceration in patients with diabetes mellitus [Harding et al., 1998]. Ideally, using thermographic measurements to prevent foot ulceration by studying and documenting thermal findings in lower extremities in well-designed clinical studies [Lavery et al., 2004] would be a very useful extension of the use of the technique. Blood vessels close to the skin surface can be easily traced from IR images [Jones et al., 2007] that are sensitive to the heat from blood vessels. [Merla et al., 2002] used IR thermography to assess vasoconstrictive responses to cold stress for patients with Raynaud phenomenon in a pilot study. One of the significant findings of this study was that it permitted the effect of treatment to be followed up.

High-sensitivity IR cameras are available, although at an increased cost. IR thermography has poor specificity: thermographic images cannot identify the increased cutaneous perfusion. The presence of inflammatory effects in both deep and superficial vessels can be misleading when

using the IR technique as indeed would the presence of nonvascular pathology such as Baker cyst of the knee joint. IR measurements can complement other modalities. Dynamic area telethermometry is a useful biomedical technique based on IR imaging and can be used to assess diabetes mellitus [Anbar et al., 1998]. It employs assessment of hemodynamic and neurogenic variations in the tissue and offers an objective and quantitative diagnostic figure of merit.

3.5. Appropriate thermal camera selection

The object of this section is to define the thermal camera that will be used for imaging the plantar foot surface of diabetic persons. Before choosing the camera, it is important to define its main characteristics.

3.5.1. Camera selection in diabetic foot

Parameters for Thermal Camera Selection
In a thermal camera (Fig. 3.11), the thermal IR radiations (A) coming from an object are focused by the optics (B) onto an infrared detector (C). The detector sends the information to sensor electronics (D) for image processing. The electronics translate the data coming from the detector into an image (E) that can be viewed in the viewfinder, on a standard video monitor or LCD screen. Infrared thermography is the art of transforming an infrared image into a radiometric one, which allows temperature values to be read from the image. So every pixel in the radiometric image is in fact a temperature measurement.
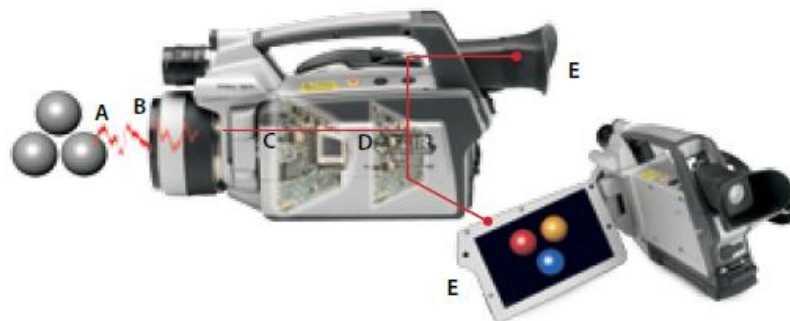
Figure 3.11: Typical IR camera: FLIR system AB [FLIR, 2011]

Basically five key requirements are important when choosing a thermal camera: 1. Camera resolution; 2. Thermal sensitivity; 3. Accuracy; 4. Spectral range, 5. Emissivity [FLIR, 2011].

1. Camera Resolution

Image resolution is an important factor. The most affordable entry models have a resolution of 60 x 60 pixels, while the advanced high end models have a resolution of 640 x 480 pixels. For more advanced inspections the 640 x 480 pixels resolution is becoming the standard for professional thermographers. A higher resolution camera can cover a larger object with only one image. With lower resolution more images are needed to cover the same area with the same level of details.

2. Thermal Sensitivity

Thermal sensitivity describes how small a temperature difference the camera can detect. The better the thermal sensitivity is, the smaller the minimum temperature difference the thermal imaging camera can pick up and visualize. Usually the thermal sensitivity is described in °C or mK. The most advanced thermal imaging cameras for industrial applications will have a thermal sensitivity of 0.03°C (30 mK). Being able to detect these minute temperature differences is important in most thermal imaging applications. High camera sensitivity is particularly important for all applications where temperature differences are low. These small temperature differences can be crucial information both for diagnosing the problem and for planning further actions.

3. Accuracy

All measurements are susceptible to error, and unfortunately thermal imaging temperature measurements are no exception. This is where the thermal imaging accuracy comes into play. In thermal imaging fact sheets, the accuracy is expressed both in percentages and degrees Celsius. This is the margin of error within which the camera will operate. The measured temperature might vary from the actual temperature with either the mentioned percentage or absolute temperature, whichever is bigger. The current industry standard for accuracy is ±2%. This error is a measurement bias.

4. Spectral range

The infrared spectral domain ranges from 1µm to 1mm. The spectral range of an IR camera is lower. The camera should be adapted to the object of interest for a high signal to noise ration.

5. Emissivity

As discussed, the emissivity of the object is a very important parameter that has to be taken into account. All thermal imaging cameras for all applications allow the operator to set the emissivity. Being able to set this parameter makes a huge difference.

3.5.2. Thermal camera selection for this project

The object of this thesis work is to analyze the temperature of the plantar surface of type 2 diabetic persons using a thermal camera. The following requirements are of interest to choose this equipment.

1. Resolution

The larger foot that we consider here is 30 cm (Peruvian foot will be of interest in the medical study). The field of view will be of 40 cm: 30 cm for the foot plus a margin of 10 cm. In the other dimension, 40 cm is enough to contain both feet including a margin. The Field of view is then of 40×40 cm^2.

The smallest areas at risk are more or less a circle of 1 cm of diameter as seen in Figure 2.4. The number of measurement points of the camera should be enough to detect these areas. According to the first Shannon theorem and to value used in image processing from a practical point of view, 2 pixels are needed to see an object. It means that any camera with more than 80×80 pixels is suitable.

2. Sensitivity

On one hand, temperature variations of the plantar foot surface are of about 4°C. One the other hand, a point to point difference between right and left foot higher than 2.2°C is

considered as abnormal. Thus a sensitivity of 0.1°C is enough for the camera to detect these possible variations which are of interest.

3. Accuracy

In this work, the medical study will be performed in only one medical center using the same camera. As the accuracy is a systematic bias, and that only comparisons or differences are of interest, the bias will not be a limitation factor.
In the case where more than one is camera is used in a given study, a calibration procedure must be applied.

4. Spectral range

The average skin temperature of a healthy person in normal conditions is of 32°C. According to the Wien law, it is related to a peak wavelength number of 9.5 μm. This corresponds to the low infrared zone. The chosen camera should include the IR spectral range of the skin.

5. Emissivity

The emissivity of human skin is between 0.97 and 0.98. The chosen camera should be able to include such a data.

Also, the distance between the feet and the camera should larger than the close focus limit.

Another important feature is the price of the camera. The technology we intend to develop should be widely used. For that reason, only low price camera that fulfilled the required criteria are of interest.

Only 3 low-price cameras were selected after a first step. Their characteristics are presented in Table 3.1.

Table 3.1: Comparison table for thermal camera selection

Parameters		FLIR camera	FLUKE camera	HGH camera
		Model i5 [FLIR user manual, 2008]	**Model Ti9 [FLUKE technical data, 2010]**	**Model IRCAM 82 [HGH, 2005]**
Imaging and optical data	Field of view (FOV)	21° x 21°	23° x 17°	15° x 12°
	Close focus limit	0.6 m	0.15 m	
	Spatial resolution (IFOV)	3.71 mRad	2.5 mRad	0.8 mRad
	Thermal sensitivity/NETD	< 0.1°C	≤ 0.20 °C	0.05°C at 20°C
	Image frequency	9 Hz	9 Hz	50 Hz
	Focus	Focus free	Manual focus mechanism	
Detector data	Detector type	Focal plane array (FPA), Uncooled microbolometer	Focal plane array (FPA), Uncooled microbolometer	Focal plane array (FPA), HgCdTe, Stirling cooler
	Spectral range	7.5 – 13 μm	7.5 – 14 μm	8 – 10 μm
	Resolution	100 x 100 pixels	160 x 120 pixels	320 x 256 pixels
Image presentation	Display	2.8 in. color LCD	3.7 in. Color LCD	
Measurement	Object temperature range	0°C to +250°C	-20°C to +250°C	-20°C to +300°C
	Accuracy	±2°C or ±2% of reading, for ambient temperature 10° to 35°C	±5° C or ±5% (at 25°C nominal, whichever is greater)	±0.4% of full scale,
	Emissivity correction	Variable from 0.1 to 1.0	In software only	Selection of emissivity
Image storage	Image storage type	Mini SD Card (1 GB)	Mini SD Card (2 GB)	Hard disk
	File formats	Standard JPEG, 14 bit measurement data included	Non-radiometric (.bmp) or fully-radiometric (.is2)	BMP format
	Compatibility	Thermal CAM Reporter 8 nd. Thermal CAM Quick Reporter compatible	Smart View Software for BMP, DIB, GIF, JPE, JFIF, JPEG, PNG, TIF and TIFT.	
Data communication interfaces	Interfaces	USB Mini-B: Data transfer to and from PC	Multi format USB card reader to and from PC	RS422, 14 bits digital
	Battery type	Rechargeable Li ion battery	Internal rechargeable	
	Battery voltage	3.6 V		
	Battery operating time	Approximately 5 hours at +25 °C ambient temperature	3 to 4 hours continuous use (assumes 50%	

Power system		and typical use	brightness of LCD)	
	Charging system	Battery is charged inside the camera	Battery is charged inside the camera	
	Power management	Automatic shut-down	Sleep mode activated after 5 minutes of inactivity. Automatic power off after 30 min of inactivity.	
	AC operation	AC adapter, 90-260 VAC input, 5 V output to camera	AC adapter/charger 110 – 220 VAC	230 VAC/50 Hz
Environmental data	Operating temperature range	0°C to + 50°C	-10°C to + 50°C	+5°C to +40°C
	Storage temperature range	-40°C to + 70°C	-20°C to + 50°C	
	Humidity (operating and storage)	95% relative humidity, IEC 60068-2-30/24 hr	10% to 95% relative humidity, non-condensing.	
	Electro Magnetic Compatibility EMC	EN 61000-6-2:2005 (Immunity). EN 61000-6-3:2007 (Emission) FCC 47 CFR Part 15 Class B (Emission)	EN 61326-1:2006. FCC 47 CFR Part 15 Class B	
	Encapsulation	Camera housing and lens: IP 43 (IEC 60529)	Camera housing and lens: IP 54 (IEC 60529)	
	Bump	25 g (IEC 60068-2-29)	25 g (IEC 60068-2-29)	
	Vibration	2 g (IEC 60068-2-6)	2 g (IEC 60068-2-6)	
Physical data	Camera weight, incl. battery	0.34 Kg	1.2 Kg	5 Kg (excluding lens)
	Camera size (LxWxH)	223x79x83 mm	276x152x127 mm	360x150x160 m
	Material	• Polycarbonate + acrylonitrile butadiene styrene (PC-ABS). • Thixomold magnesium • Thermoplastic elastomer (TPE)	• Polycarbonate + acrylonitrile butadiene styrene (PC-ABS). • Thermoplastic elastomer (TPE)	Metal
Certifications	Certification	UL, CSA, CE, PSE and CCC.	UL, CSA, ISA	
Price	Price	US$ 1,595	US$ 2,195	US$ 3,465

The final choice is based on the following analysis.

The 3 cameras have all the necessary technical characteristics to be used in the study. The technical characteristics of the HGH camera are a bit better than the two others (in terms of sensitivity, and resolution). However, important features for the camera are the price, the fact that the camera should be easily transportable and the possibility of using Mini SD Card for data exchange. Taking into account the criteria and analysis above, the FLIR i5 is the best choice: it has the necessary performances combined to a very low price (1,595 US Dollars). Figure 3.12 shows the IR camera selected and Table 3.2 presents a resume of its main features.

Table 3.2: FLIR i5 model datasheet in resume

Resolution	100 x 100 pixels
Object temperature range	0°C to +250°C
Thermal sensitivity	0.10°C
Accuracy	±2%

Figure 3.12: Camera FLIR i5, the selected thermal camera

A final verification concerns the focus of the camera. The field of view (FOV) is 40 cm and corresponds to an angle of 21°. This means that the distance between the object and the camera should be of 1.1 m. The close focus limit is of 0.6 m meaning that the focus point can be reached.

3.6 Conclusion

In this chapter, industrial applications of thermography were presented, followed by the one related to medicine. The potential of thermography in this domain are of importance. The main research works in thermography for diabetic foot disorders were discussed: thermography can help in the early diagnosis of diabetes, and can reduce the incidence of foot ulcer.

The last section of this chapter dealt with the selection of the thermal camera. The FLIR i5 model was finally chosen.

3.7 Images thermiques (in french language)

Le transfert de chaleur est décrit par trois principaux modes. Le premier est la conduction, nécessitant un contact entre l'objet et le détecteur pour permettre l'écoulement de l'énergie thermique. Le second mode de transfert de chaleur est la convection où l'écoulement d'une masse chaude transfère l'énergie thermique. Le troisième est le rayonnement. Ces deux derniers modes conduisent à des méthodes de détection à distance. Les caméras thermiques sont basées sur le mode de rayonnement dans le domaine spectral de l'infrarouge (de 1 pm à 1 mm). Une fois émises, les radiations peuvent être acquises à l'aide d'une caméra infrarouge thermique.

Pour les applications industrielles, les caméras thermiques sont des outils puissants et non-invasifs de surveillance et de diagnostic de l'état des installations et des composants électriques et mécaniques. Une caméra thermique est utile pour identifier rapidement les problèmes avant de devenir plus graves et plus coûteux à réparer. Une image thermique qui comprend des données précises de la température fournit à l'expert de la maintenance des informations importantes sur l'état de l'équipement inspecté. Ces inspections peuvent être faites avec le processus de production en pleine activité.

Par exemple, les caméras thermiques sont couramment utilisées pour les inspections de systèmes et composants électriques de toute taille et de toute forme. Une caméra d'imagerie thermique permettra de localiser avec précision le problème, de déterminer la gravité du problème et d'établir le délai dans lequel l'équipement doit être réparé. De même, lorsque les composants mécaniques s'usent et deviennent moins efficaces, la chaleur dissipée augmente. En conséquence, la température des systèmes mécaniques défectueux ou en vibration va augmenter rapidement avant la panne. L'imagerie thermique donne un aperçu complet et permet de détecter une multitude de défauts.
Les revêtements réfractaires pour les fours, chaudières et incinérateurs sont sujets à la dégénérescence et la perte de performance. Avec une caméra d'imagerie thermique, un matériau réfractaire endommagé et la perte de chaleur correspondante peuvent être facilement localisés, comme la transmission de chaleur apparaîtra clairement sur une image thermique.

La thermographie est une méthode non-invasive et sans contact de projection de la température de la surface de la peau qui est économique, rapide et qui n'inflige pas de douleur à la personne. Il s'agit d'une approche de formation d'image relativement simple qui détecte la variation de la température à la surface de la peau humaine. La thermographie est largement utilisée dans le domaine médical, comme la thermographie préventive du cancer du sein, le contrôle des inflammations dans la polyarthrite rhumatoïde, la détermination du degré de

sévérité de la maladie de Raynaud, l'évaluation de l'arthrose du genou ou encore le diagnostic en chirurgie plastique et reconstructive.

Les images thermiques dans le pied diabétique

La température est une caractéristique importante dans le pied diabétique. L'imagerie thermique est donc une candidate sérieuse pour détecter les changements de température dans les troubles du pied diabétique. La mesure de la température de la voûte plantaire en utilisant l'infrarouge permet de discerner une petite différence thermique au-delà de la limite palpable, en particulier pour les patients sans symptômes inflammatoires graves. L'identification des risques est un élément fondamental dans la gestion des soins de santé préventifs des patients diabétiques ayant des problèmes potentiels de pied.

Différentes études ont permis de montrer que la température de la peau et ses variations permettaient de détecter des lésions tissulaires aiguës (par exemple un ulcère), liées à la maladie des patients. Les températures mesurées, point à point ou moyennées, ont ainsi été comparées à une température de référence, ou été comparées entre elles, ou encore comparées entre les deux pieds du patient. Des régions d'intérêt de la voûte plantaire ont aussi été définies pour réaliser des études régionales. Tous les patients ont également subi des examens annexes afin de déterminer leur(s) maladie(s) et le niveau de risque de leur diabète. Plusieurs classifications ont ensuite été proposées suivant le degré de risque ou la (les) maladie(s) et les mesures de température ou les variations.

Ainsi l'évaluation de la température semble offrir un mécanisme permettant d'identifier un signe précoce de lésion, quand il est encore temps d'éviter une blessure. La détection de l'augmentation de la température et la prescription d'un traitement adéquat peut réduire l'incidence de l'ulcère du pied par 3. Des variations de motifs thermographiques plantaires chez les patients diabétiques non ulcéreux ont été présentées et des essais ont été faits pour tenter de trouver une corrélation entre ces motifs et les classifications évoquées ci-dessus.

Dans une caméra thermique, les rayonnements infrarouges thermiques provenant d'un objet sont focalisés par une optique sur un détecteur infrarouge. Le détecteur envoie les informations au capteur électronique qui convertit les données en une image qui peut être visionnée sur un moniteur vidéo standard ou un écran LCD. Fondamentalement, cinq critères clés sont importants lors du choix de la caméra thermique : sa résolution, sa sensibilité thermique, sa précision, son domaine spectral et son émissivité.

L'objet de ce travail de thèse est d'analyser la température de la surface plantaire de personnes diabétiques de type 2 à l'aide d'une caméra thermique. Une autre caractéristique importante est le prix de la caméra. La technologie que nous entendons développer devrait être largement utilisée. Au vu de ces critères, après une première étape de sélection, notre choix s'est porté sur la caméra FLIR i5 qui présente les performances nécessaires combinées à un prix très bas.

4. Thermal analysis for diabetic foot

This chapter concerns the acquisition protocol that will be used in the clinical study, and is also related to the description of the image processing of the plantar foot thermal images realized for this project.

4.1. Acquisition protocol

4.1.1. Technical requirements for foot image acquisition

The arrangement of the elements is presented in Figure 4.1. Remember that the distance between the camera and the feet was chosen to 1.1 m in the previous chapter.
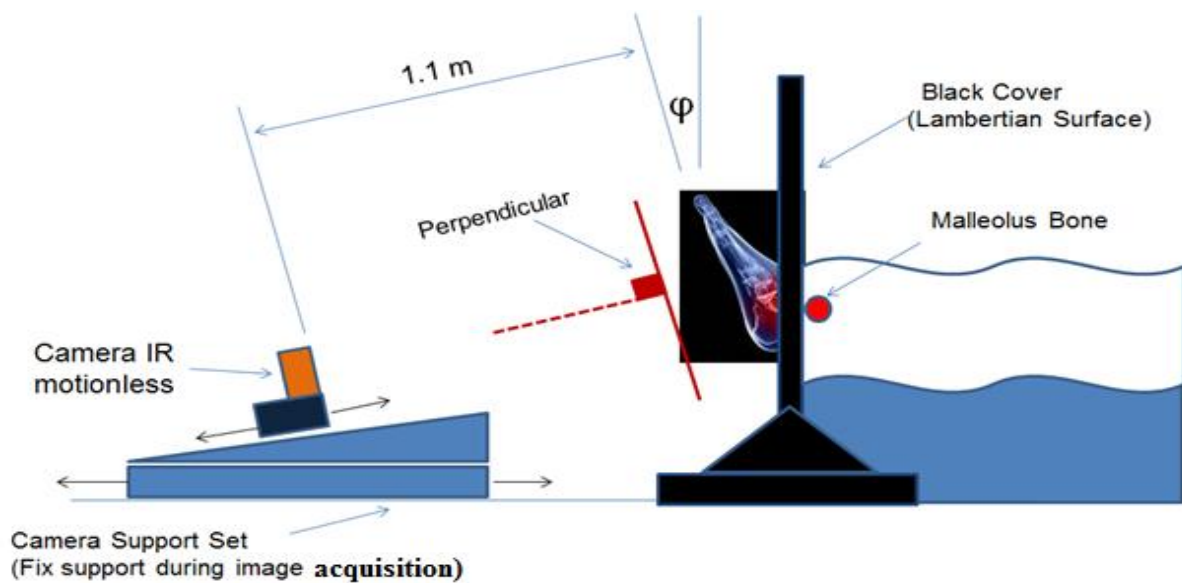
Figure 4.1: Arrangement of elements for image acquisition

Thermal reflections are a common source of problems in interpreting infrared thermal images. In particular, smooth surfaces like glass, metals or wet surfaces, but also brick and concrete may easily give rise to reflections of infrared radiation from often uncared sources. If unnoticed, these thermal reflections may give rise to misinterpretations of the object temperature [Henke et al., 2004]. For perfect diffusely scattering surfaces, the Lambertian reflectance is the property that defines an ideal diffusely reflecting surface. The apparent brightness of such a surface to an observer is the same regardless of the observer's angle of view (Figure 4.2). More technically, the surface's luminance is isotropic, and the luminous intensity obeys Lambert's cosine law.
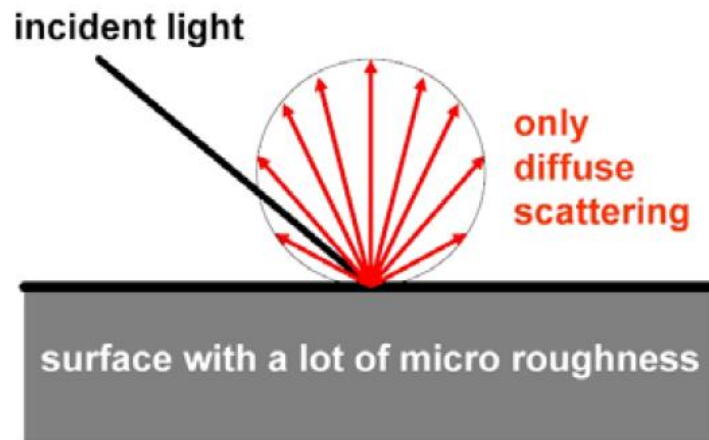
Figure 4.2: Lambertian surface [Henke et al., 2004]

Not all rough surfaces are Lambertian reflectors, but this is often a good approximation when the characteristics of the surface are unknown. The polyurethane foam has a surface roughness estimated in 0.8 [Yu, 2010].

The polyurethane cover plate is a good approximation of a Lambertian surface. Its bidirectional reflectance distribution function (BRDF) that describes the appearance of a material by its interaction with light at a surface point [Ngan, A., 2005] is showed in Figure 4.3, where the reflectance distribution is fairly uniform at all angle of incidence.
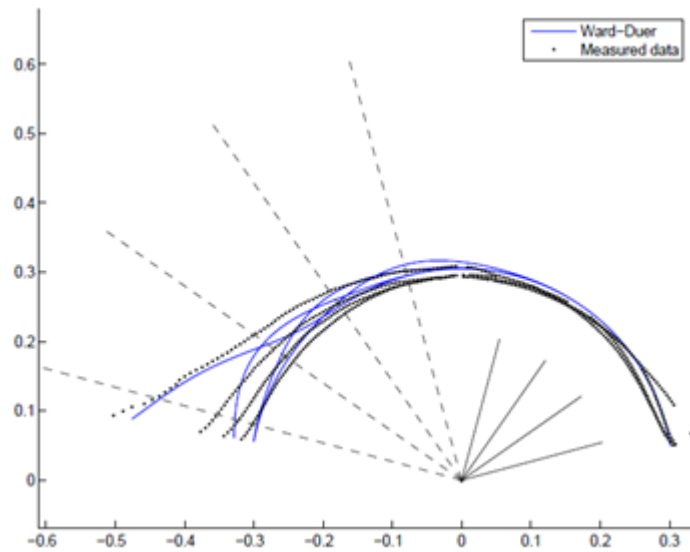
Figure 4.3: Bidirectional Reflectance Distribution Function (BRDF)
for polyurethane foam using the Ward-Duer model [Ngan A., 2005]

The cover of polyurethane foam will have the following physical characteristics: density=19.2 Kg/m^3 (1.2 lb per cubic ft.); tensile strength= 34.5- 51.7 kPa (5.0 – 7.5 lbs/sq. in). It should be larger than 40×40 cm^2, which is the chosen FOV.

Additionally, the cover of polyurethane must adapt to the feet in the ankles. This requires performing two holes so that the feet can be positioned. The following Figure 4.4 shows the dimensions and layout of the holes in the cover of polyurethane.
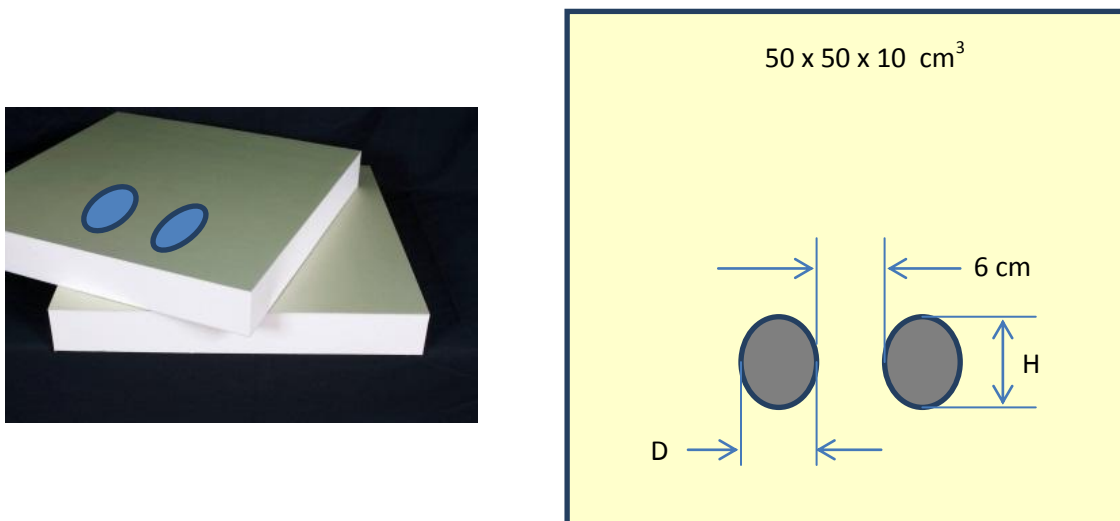
Figure 4.4: Cover of polyurethane with dimensions and holes:
D x H: small 6 x 8 cm and medium 6 x 10 cm

The holes in the polyurethane foam should follow the profile of the ankles to avoid disturbances in the thermal image. Figure 4.5 shows the effect of this perturbation.
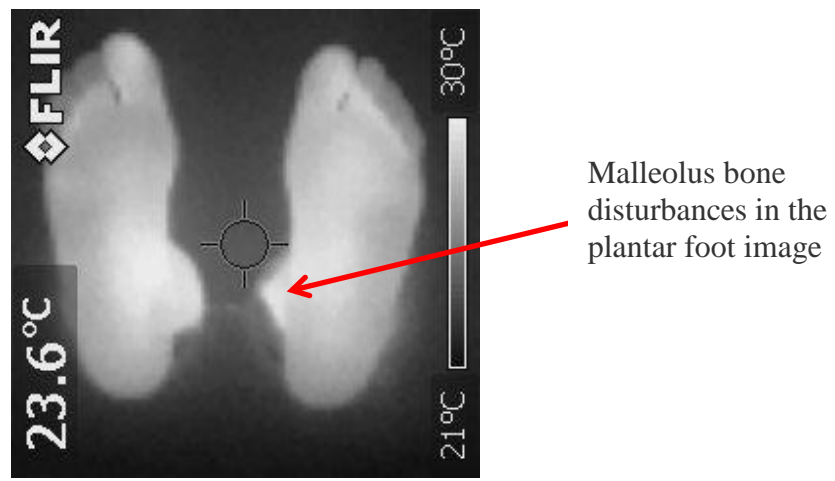
Figure 4.5: Example of malleolus bone disturbances in plantar foot image

Finally, in the experimental tests, we found that it is better to shoot as possible in the dark to avoid any effect of reflection of objects in the environment. Also, when taking the picture and press the button on the camera, avoid camera movement. It is also recommended to fix the camera with the utmost care.

4.1.2. Foot image acquisition protocol

The Image Acquisition Protocol for this project considers the following aspects:
- Preparation of the room;
- Environmental controls;
- Equipment and materials;
- Preparation of patient; and
- Image acquisition procedure.

Preparation of the room

As part of image quality control, the design and environmental conditions of the room should conform to the thermodynamic attributes required in thermal image acquisition. The room itself should be of adequate size to maintain a homogenous temperature. There must be sufficient space for the placement of equipment and freedom of movement for both the technician and patient. It should also be large enough to allow for patients of all sizes to be positioned adequately for each anatomic image of foot. A room of approximately 3 x 4 m, or dimensions similar in square meter, is adequate to meet these requirements. Larger rooms may also be used as long as a steady ambient temperature can be maintained (see Environmental Controls below). During the examination, the patient should be able to be placed relatively equidistant and adequately spaced from each wall. The room should be carpeted. If this is not possible, a well-insulated area rug will suffice.

A complete infrared survey of the room should be performed to inspect for any infrared sources and leakage (i.e. windows, heating ducts, light fixtures, hot water pipes, …). Any significant findings need to be remedied. All windows must be covered or shielded to prevent outside infrared radiation from entering the room. Shades or blinds may be adequate for this purpose depending on the amount of direct infrared radiation. Windows and doors should be adequately sealed to prevent airflow in the area where the patient is positioned. Heat and air conditioning sources must be minimized in the room and kept well away from the patient. Vents should be directed away from the patient and thoroughly diffused or turned off during the examination. Incandescent lighting should not be used during the examination due to the amount of infrared radiation produced. Standard fluorescent lighting is adequate.

Environmental Controls

The temperature of the room should be such that the patient's physiology is not altered to the point of shivering or perspiring. The temperature range should be maintained between 18 and 23 °C. Room temperature changes during the course of an examination must be gradual so that steady state physiology is maintained and all parts of the body can adjust uniformly. The temperature of the room should not vary more than 1°C during the course of a study. The humidity of the room must also be controlled such that there is no air moisture built up on the skin, perspiration, or vapor levels that can interact with radiant infrared energy. The examining room must have an ambient temperature thermometer to accurately monitor the temperature of the room.

Equipment and materials

For the purposes of this project, it is necessary to have the following equipment and materials:

- Infrared camera selected as in Chapter 3;
- Tripod to support the IR camera;
- Measuring tape of 2 m;
- Polyurethane foam with holes as in Figure 4.6;
- Plastic bags to cover each foot when the polyurethane foam is placed or removed.

| IR Camera | Tripod | Measuring tape | Polyurethane foam | Plastic bags |
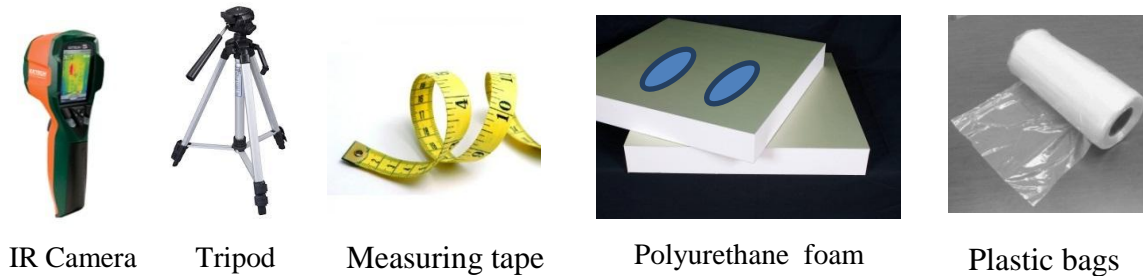
Figure 4.6: Equipment and materials for image acquisition

Preparation of the patient

Proper management of the patient, both before and during the examination, decreases the chance of thermal artifacts and increases the accuracy of the images.

Pre-examination preparation instructions are of great importance in decreasing thermal artifacts. The following is a minimal list of instructions that should be given to the patient prior to the examination:

- No sun bathing of the plantar area of foot to be imaged 5 days prior to the exam.
- No use of lotions, creams or powders on the plantar area to be imaged the day of the exam.
- No physical therapy, EMS, TENS, ultrasound treatment, acupuncture, chiropractic, physical stimulation, hot or cold pack use for 24 hours before the exam.
- No exercise 4 hours prior to the exam.
- If bathing, it must be no closer than 1 hour before the exam.
- If not contraindicated by the patient's doctor, avoid the use of pain medications and vasoactive drugs the day of the exam. The patient must consult his doctor before changing the use of any medications.

Intake forms should be used and formatted to take notes about examination, and register a current and past history of any diagnoses and traumas.

Concerning the patient acclimation, prior to imaging, the patient's body must be given sufficient time to equilibrate with the ambient conditions of the laboratory such that an approximate steady physiologic state of thermodynamic equilibrium can be reached. A minimum equilibration period of 15 minutes should be observed [Sun et al, 2006][IACT, 2002]; further equilibration results in minimal surface temperature changes. During the equilibration period and the subsequent examination, the area to be imaged should remain completely uncovered of clothing or jewelry.

Let's feet patient in environment for 15 min.

Hold camera on tripod.

Vertical alignment on screen. Move the tripod.

Place plastic bags before place the foam.

Place the foam to patient, covering completely the malleoli. Align the feet. Remove plastic bags.

Turn off ambient light.

Press the button without moving the camera.

Register several images per patient.

Use plastic bags to remove foot.

Figure 4.7: Recommendations for a robust acquisition of thermal images of plantar foot

Result

Figure 4.8 shows an image obtained using the image acquisition protocol developed in this chapter. The background is homogeneous, and only the plantar foot surface appears as a homogeneous white region. However, the edges of the image are not very sharp.
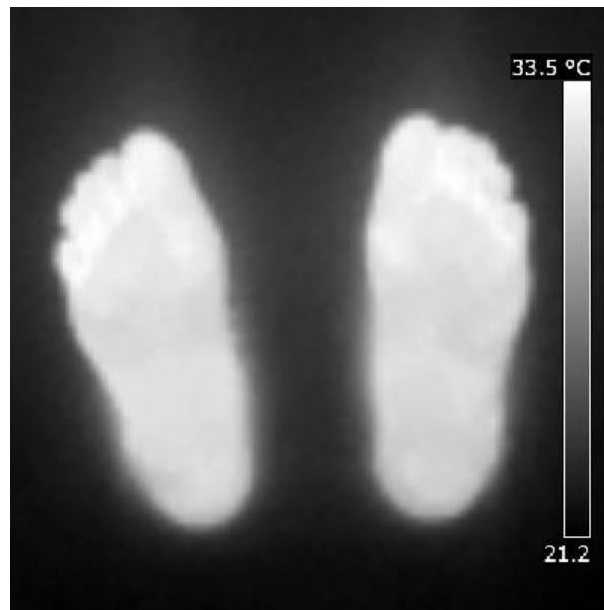
Figure 4.8: Thermal image taken with the proposed acquisition protocol

To confirm this analysis, Figure 4.9 is the histogram of the image in Figure 4.8. The grey levels on the x-axis vary from 0 to 255. 0 corresponds to a temperature of 21.2 °C while 255 to 33.5°C.

This histogram is bimodal as expected. The background is homogeneous in the range 22 to 25°C. The plantar foot surface temperature is in the range 30 to 33°C. There are a large number of pixels between these two main modes difficult to classify. The segmentation method should take this into consideration.
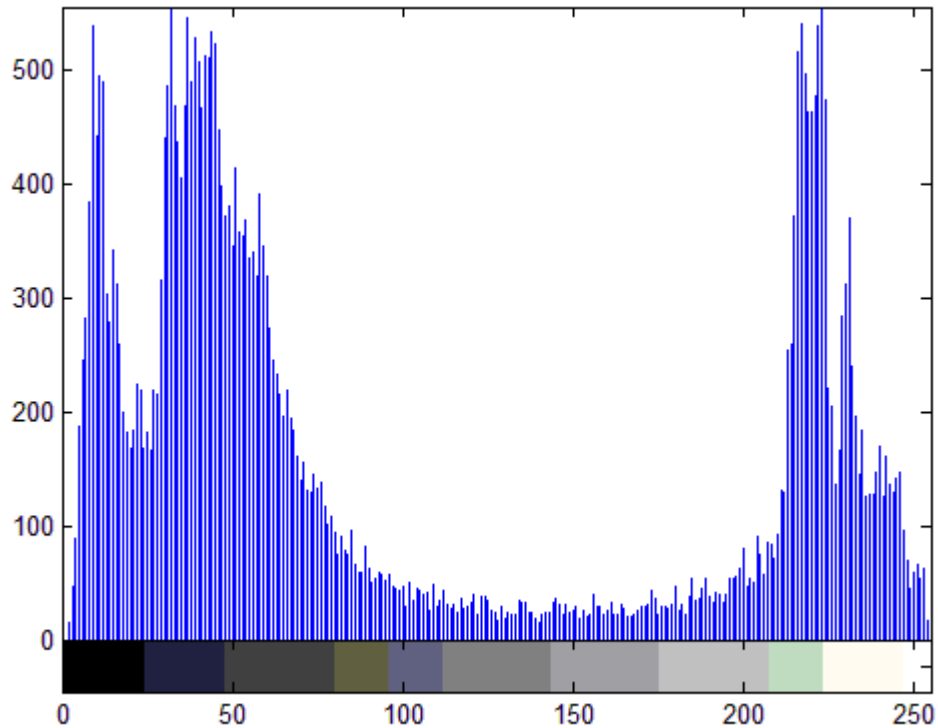
Figure 4.9: Histogram of the image in Figure 4.8

4.2. Image processing for thermal foot images

The input image of the image processing method is a plantar thermal foot image as that of Figure 4.8. It is an image of 600×600 pixels. Indeed, from the 100×100 pixels image of the FLIR i5 sensor, an interpolation is performed into the camera to provide this 600×600 pixels image.

In the image, there is also a temperature bar on the right indicating the maximal and minimal temperature in the image.

The image processing will be composed of several steps:
- Pre-processing to remove the labels and separate the two feet,
- Segmentation of the feet.

From this, the mean and the standard deviation of the plantar foot surface of the right and left feet will be calculated. They are named MR, ML, SR, and SL, respectively.

In addition, the point to point difference is of interest. Remember that temperature of corresponding area of the right and left foot do not usually differs more than 1°C in diabetic foot. A temperature difference greater than 2.2°C is considered as a sign of a possible foot ulcer. Detecting this increased temperature between the right and left foot is important. The absolute difference between the two feet will be assessed: it will be named $|\Delta T°|$. The percentage of points with a $|\Delta T°|$ is greater than 2.2°C will also be of interest and will be named %.

To do so, additional steps are needed in the image processing software:

- Mirror image of left foot (in the following description, this step will be included in the pre-processing task),
- Registration of the two segmented feet,
- Assessment of the point to point thermal difference,
- Computation of the mean absolute difference between the right and left foot and the percentage of pixels such that $|\Delta T°|$ is higher than 2.2°C.

Pre-processing

Labels are first discarded. This operation is simple since their positions and shapes are known.

Following this operation, the minimum of the valley observed in the radon transform in the vertical direction is found. It is used to split the image in two sub-images, as shown in Figure 4.10.

The next step is to calculate the mirror image of left foot image (Figure 4.11). It is the preparation of the segmentation and registration steps.
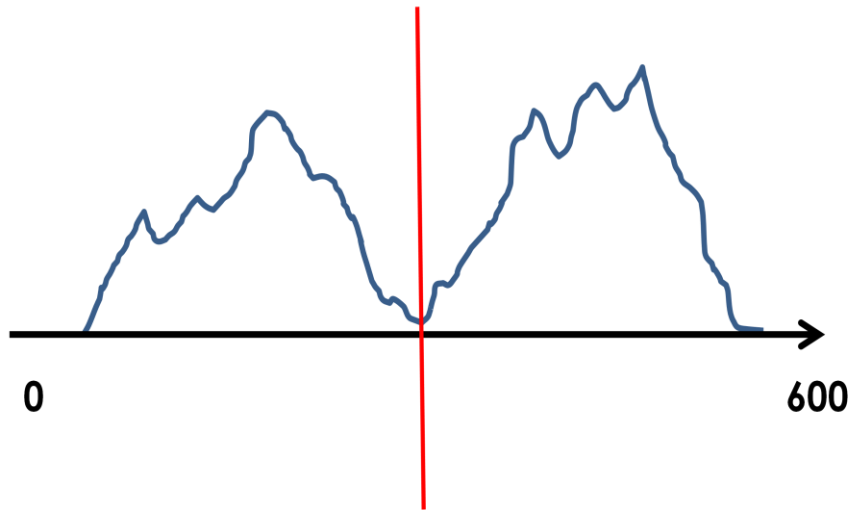
Figure 4.10: Radon transform in the vertical direction and sub-images of the right and left feet shown in Figure 4.8

Left foot   **Mirror image of the left foot**
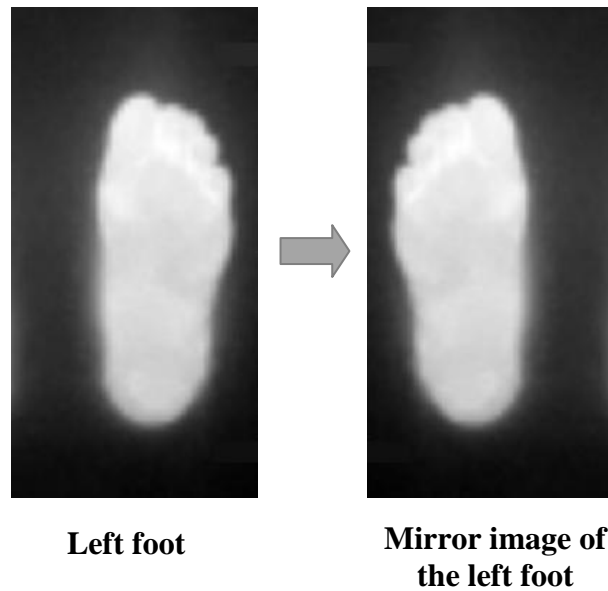
Figure 4.11: Mirror image of the left foot in Figure 4.10

4.2.1. Segmentation

There are several common methods for segmentation, such as edge detection, region growing, and more recently active contours.

Active contours are classes of methods which iteratively modify an initial contour to fit the desired contour. It corresponds to the minimum of a so-called energy function. We choose to implement the Chan and Vese segmentation method [Chan et al., 2001]. It is particularly adapted when contours are not sharp as it is the case of this study. Chan and Vese have proposed an energy function based on grey level of pixels inside and outside the contour. Results are shown in Figure 4.12 where the iteration number is 300. The initial contour is a circle in the middle of the image of 150 pixels of diameter.

300 iterations   **300 iterations**

Region and contour of the right foot   **Region and contour of the left foot**
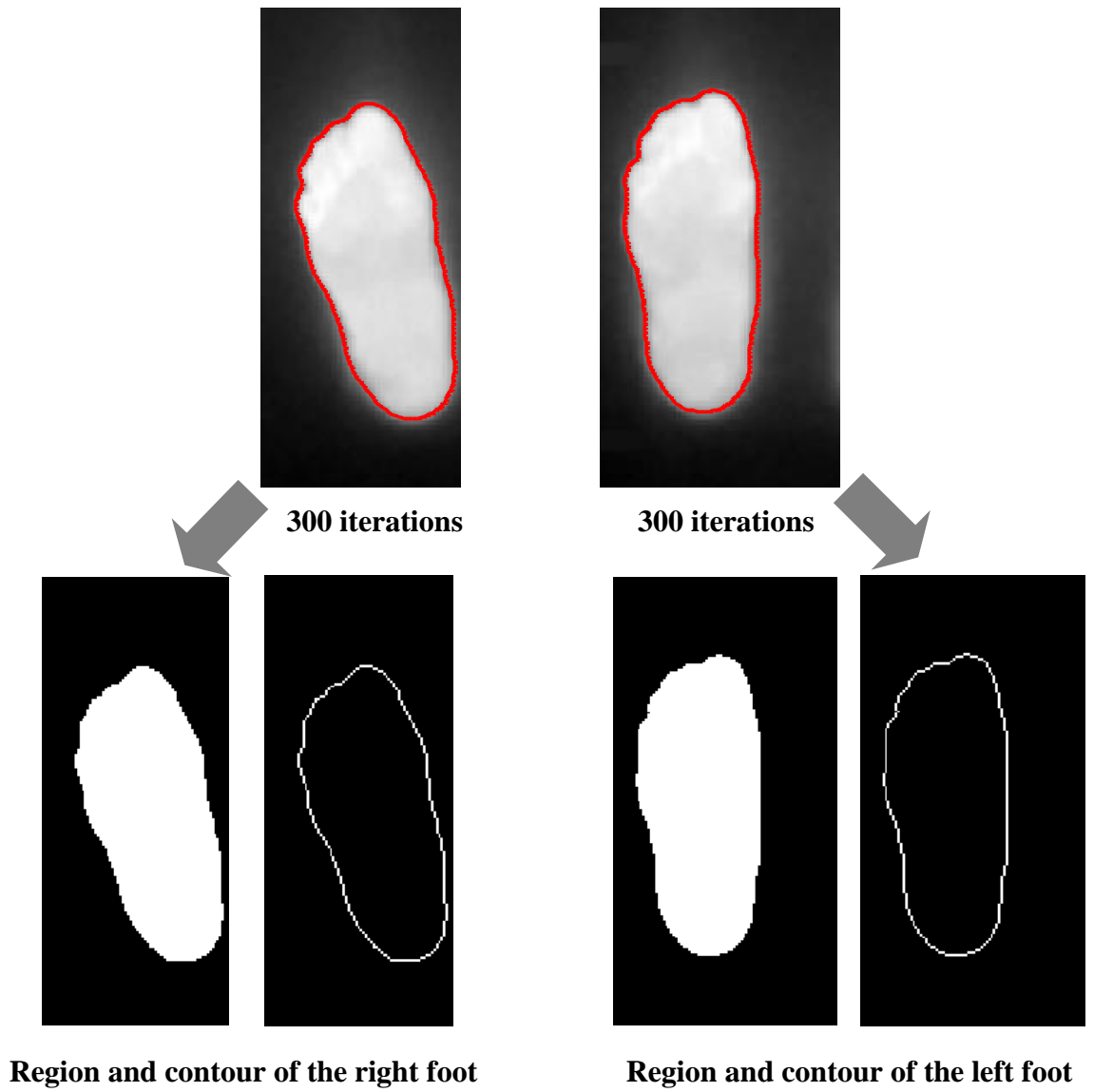
Figure 4.12: Chan and Vese segmentation with 300 iterations

Results obtained after this segmentation step are of high quality.

4.2.2. Registration

There are two classes of registrations: the first is the rigid registration when the object is only translated and/or rotated to fit another object more or less identical. The other kind of registration is non rigid registration where, in addition to a possible translation and/or rotation, one of the objects is locally deformed to fit the other. For the application of thermal image foot registration, the rigid registration was chosen. Indeed, it was considered that left and right feet are very similar. In addition, it was observed that, in case of acquisition problems in the malleolus region or in the roes region, results were better using rigid registration.

Iterative Closest Point (ICP) algorithm is a straightforward rigid registration method [Besl, 1992]. We choose this algorithm because it is efficient and easy to implement.

Results presented in Figure 4.13 are of high quality. The two feet contours are almost identical.
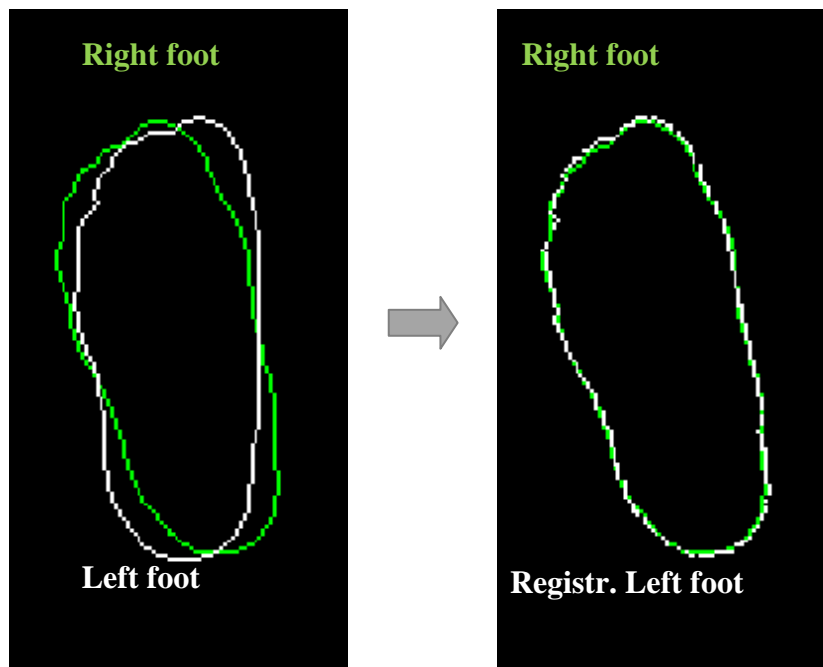
Figure 4.13: Result of ICP registration for image in Figure 4.8

The final step is the calculation of the difference of temperature between the right and left feet. Figure 4.14 shows the image of the absolute temperature difference between the 2 feet. Only common pixels to the right and left feet are kept.
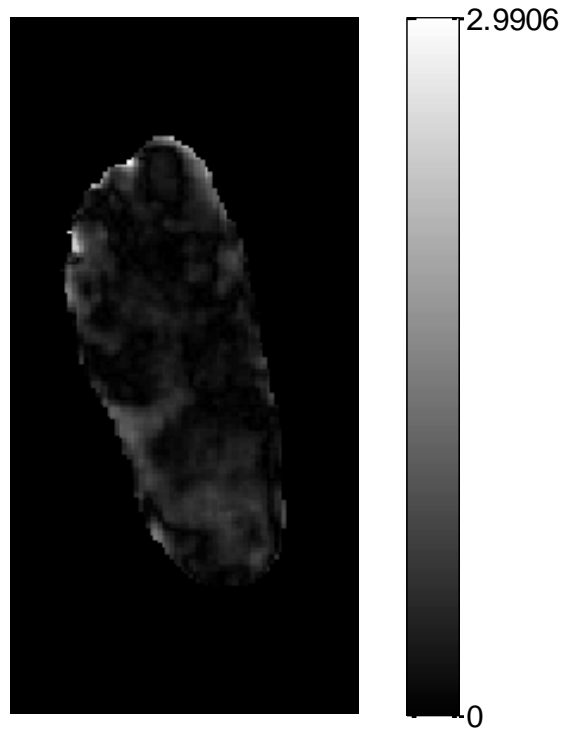
Figure 4.15: Point to point absolute difference image as well as the related temperature bar
of image shown in Figure 4.8

This difference of temperature is in the range 0 to 3°C. The highest temperature differences
are close to the feet contours.

From images in Figures 4.10 and 4.15, the following parameters are assessed:

- $|\Delta T°|$ value (mean absolute value of the point to point difference between left and
  right feet),
- % (percentage of points such that $|\Delta T°|$ is greater than 2.2°C),
- ML: mean left temperature,
- MR: mean right temperature,
- SL: standard deviation of left foot,
- SR: standard deviation of right foot.

The image processing software is written using Matlab along with its image processing
toolbox.

4.3 Conclusion

In this chapter, the acquisition protocol to ensure a high reproducibility of the results was presented. The thermal image of the plantar foot is as a light region surrounded by a homogeneous dark background.

The image processing is composed of three steps: preprocessing, segmentation, and finally registration. From these steps, various parameters can be estimated.

The object of the following chapter is to study the interest of such parameters when type 2 diabetes persons are analyzed using a thermal camera.

4.4 L'analyse thermique pour le pied diabétique (in french language)

Ce chapitre présente le protocole d'acquisition utilisé dans l'étude clinique et décrit le traitement des images thermiques plantaires réalisé pour ce projet.

Les réflexions thermiques sont une source fréquente de problèmes dans l'interprétation des images thermiques infrarouges. En particulier, les surfaces lisses comme le verre, les métaux ou les surfaces humides, peuvent facilement donner lieu à des réflexions de rayonnement infrarouge à partir de sources souvent négligées. Si elles ne sont pas prises en compte, ces réflexions thermiques peuvent donner lieu à des interprétations erronées de la température de l'objet. Dans le cadre de nos acquisitions, il faut éviter toute perturbation extérieure qui pourrait conduire à une mauvaise lecture des températures des pieds : une plaque en mousse de polyuréthane présentant les propriétés d'une surface lambertienne et ayant une luminosité apparente pour un observateur identique quel que soit l'angle d'observation est placée autour des chevilles du patient pour éviter des perturbations dans l'image thermique. De plus, il est préférable d'acquérir les images dans la plus grande obscurité pour limiter tout effet de réflexion des objets dans l'environnement.

Quant au protocole d'acquisition d'image, il doit prendre en compte différents aspects. Pour une bonne qualité d'image, la conception et les conditions environnementales de la salle dans laquelle la caméra montée sur trépied est installée doivent être conformes aux caractéristiques thermodynamiques nécessaires à l'acquisition d'image thermique. La pièce doit également être d'une taille suffisante pour pouvoir manipuler dans de bonnes conditions mais aussi pour

maintenir une température homogène. En effet, la plage de température doit être maintenue entre 18 et 23 ° C et ne doit pas varier de plus de 1 °C au cours d'un examen, avec un niveau d'humidité pas trop élevé afin de limiter les interactions avec l'énergie infrarouge rayonnante.

Une bonne gestion du patient, à la fois avant et pendant l'examen, diminue le risque d'artefacts thermiques et augmente la précision des images. Pour ce faire, un certain nombre de points, tels que la non utilisation de lotions, de crèmes ou de poudres sur la zone plantaire le jour de l'examen ou aucun exercice physique 4 heures avant l'examen, sont à vérifier. Il faut également respecter une période d'acclimatation d'environ 15 min. du patient afin d'obtenir un équilibre thermodynamique.

Un formulaire d'inscription doit être utilisé et mis en forme pour prendre des notes au sujet de l'examen, et permettre d'enregistrer l'histoire actuelle et passée de tous les diagnostics et traumatismes du patient.

L'image thermique acquise nécessite un traitement particulier afin de fournir quelques résultats au docteur. Les étiquettes sont d'abord éliminées : cette opération est simple puisque leurs positions et formes sont connues. Il faut ensuite séparer le pied gauche du pied droit et réaliser une segmentation de chacun des deux pieds : la méthode de segmentation par contours actifs proposée par Chan & Vese est utilisée ici car elle est particulièrement adaptée lorsque les contours ne sont pas nets.

Afin de pouvoir superposer les deux pieds et faire un comparatif, un recalage rigide est ensuite réalisé entre les deux pieds, ceux-ci étant considérés comme assez similaires. L'algorithme itératif du point le plus proche (ICP) est appliqué ici car il est efficace et facile à mettre en œuvre. La dernière étape est le calcul de la différence de température $|\Delta T°|$ point à point entre les pieds droit et gauche. D'autres paramètres sont également calculés, tels que le pourcentage de pixels pour lesquels $|\Delta T°|$ est supérieur à 2,2 ° C, la température moyenne et l'écart type de chacun des pieds.

	V
CHAPTER	

5. Medical study

The overall object of the project is to find new strategies to improve the early diagnosis of diabetic foot from the analysis of thermal images. Thus a transversal clinical study has been conducted including a population of type 2 diabetes before a possible ulceration occurs.

5.1. Material

Hospital National Dos de Mayo (HNDM), Lima, Peru, has authorized the completion of this study and all of the patients provided informed written consent. The Ethic committee "Office support for teaching and research" OADI and the clinical responsible Dr. Hugo César Arbañil Huamán have approved the 15th of February 2012 the agreement N°190 named: "Determination of the predictive diagnosis capacity for late injures of diabetic foot using periodic reviews of thermography". This agreement in Spanish language is reported in appendix B.

The inclusion, exclusion and withdrawal criteria used in the medical study are the following.

Inclusion criteria:
- Patients aged over 30 years diagnosed with type 2 diabetes.
- Patients of both sexes.
- Patients who consent in writing for inclusion in the study.

Exclusion criteria:
- Patient with ulcer.
- Patients with neurodegenerative diseases.
- Patients in the pediatric age.
- Current presence: acute pancreatitis, acute colecistitis, obstructive jaundice or cholangitis.
- Hereditary spherocytosis.

- Pregnant or lactating women.
- Patients with intention to donate blood during the study.
- Failure to give informed consent.
- Patients participating in other research studies.
- Presence of onco-proliferative processes and / or decompensated chronic ischemic heart disease, diabetes mellitus (ketoacidosis and / or diabetic coma), renal insufficiency (creatinine > 200 mmol / L + oligoanuric).
- Holders of psychiatric illness that prevented him/her from giving informed consent.

Criteria for withdrawal:
- Patients may be withdrawn from the study for any of the following reasons:
  1.- The patient decides not to continue in the study and / or follow-up visits;
  2.- The patient does not cooperate or fails the criteria for follow-up.
- Patients with uncontrolled hypertension are removed from the study.

The type 2 diabetic patients who came from outside the hospital for a regular exam in the diabetes service of the HNDM were first taken in charge by experimented nurses. Information about their age, gender, the time on which they were first diagnosized as type 2 diabetic patient (time of diagnosis), and their body mass index were collected. They had information about the project and signed the informed written consent. Following this, the same medical doctor (Dr Julio Torres) conducted the medical assessment as described in Table 2.3 for all patients of the study. He completed the two classifications already described. The first one is the by-risk classification:

- Low risk,
- Medium risk,
- High risk.

The other one is the by-disease classification:

- Healthy (neither ischemia nor neuropathy),
- Ischemia,
- Neuropathy,
- Mixed (ischemia + neuropathy).

This bear foot medical exam is lasting about 30 minutes. This time is longer than the 15 minutes for thermal equilibrium requested in the acquisition protocol. Thus the patients went immediately in a room next to the doctor office. This 4×3 m^2 room has a temperature of 23°C $\pm$ 3°C. During the exam, the temperature was not varying more than 0.5°C.

The acquisition protocol described in chapter 3 was applied. The acquisition was performed by an experimented nurse from the hospital who took care of the patient. Another person of the Pontificia Universidad Catolica del Peru took care of the camera and was in charge of the image acquisition.

85 such exams were performed from 1 February 2013 to 30 June 2013 in the Dos de Mayo hospital.

5.2. Results

5.2.1 Data analysis

The corresponding 85 images are presented in appendix C.
Even if the standardized protocol was applied, one can see that the variability is high in the shapes, orientations, textures, and contours of this database.

Appendix D shows the classification of the 85 persons, and results of the parameters that were computed on these data**.**

To be statistically significant, a group should be composed of more than 30 persons.

In the by-risk classification, the number of patients with Low risk is too little (only 3). The statistical analysis of this population is to be taken with the utmost care.

In the by-desease classification, nobody was classified as Ischemia. In addition, the number of Mixed is small, and the number of Healthy is too little (only 5).

Next tables present the mean and standard deviation of the age, time of diagnosis and body mass index (BMI) in the 3 by-risk groups and in the 3 by-disease groups that were observed, respectively.

Table 5.1: Mean and standard deviation for the age, gender, time of diagnosis and body mass index (BMI) using the by-risk classification (top) and the by-disease classification (bottom)

Patient Characteristics				
Variables	**General**	**By-risk classification**		
		Low	**Medium**	**High**
Samples	**85**	3	49	33
Age (yr)	**63.18 ± 10.56**	55.67 ± 10.07	62.55 ± 10.86	64.79 ± 10.03
Gender (F / M)	**56 / 29**	2 / 1	34 / 15	20 / 13
Time Diagnosis (yr)	**10.19 ± 8.51**	8.67 ± 6.03	6.97 ± 5.83	15.11 ± 9.77
BMI (Kg/m²)	**29.74 ± 5.32**	30.29 ± 11.86	30.37 ± 4.74	28.76 ± 5.49

Patient Characteristics				
Variables	**General**	**By-disease classification**		
		Healthy	**Neuropathy**	**Mixed**
Samples	**85**	5	63	17
Age (yr)	**63.18 ± 10.56**	58.20 ± 8.41	61.84 ± 9.80	69.59 ± 11.68
Gender (F / M)	**56 / 29**	2 / 3	44 / 19	10 / 7
Time Diagnosis (yr)	**10.19 ± 8.51**	4.02 ± 3.06	9.15 ± 6.59	15.86 ± 12.61
BMI (Kg/m²)	**29.74 ± 5.32**	28.49 ± 5.83	29.76 ± 5.22	30.04 ± 5.83

5.2.2 Statistical analysis

To assess if a difference occurs between these various groups, a Student's t-test is performed with a level of significance α=0.05 on the age, time of diagnosis, and BMI.

Table 5.2 and 5.3 show the results.

In the by-risk classification, only the time of diagnosis between the High and Medium population (Table 5.2) is different between the two groups (t=4.295). It is 15.1 years for the High risk, and 6.9 years for the Medium risk. This means that time of diagnosis is an important feature regarding the by-risk classification.

Table 5.2: Statistical t for age, time of diagnosis and body mass index (BMI) using the by-risk classification

	By-risk classification					
Alpha: 0.05	High			Low		
	Age		Time of Diagnosis		BMI	
Means	64,788	55,667	15,109	8,667	28,765	30,291
Variances	100,672	101,333	95,545	36,333	30,110	140,578
Statistical t	1,503		1,663		-0,221	
P(T<=t) one-tail	0,136		0,097		0,423	
Critical value of t (one-tail)	2,920		2,353		2,920	
P(T<=t) two-tail	0,272		0,195		0,846	
Critical value of t (two-tail)	4,303		3,182		4,303	
Alpha: 0.05	High			Medium		
	Age		Time of Diagnosis		BMI	
Means	64,788	62,551	15,109	6,971	28,765	30,368
Variances	100,672	117,919	95,545	34,033	30,110	22,510
Statistical t	0,958		4,295		-1,369	
P(T<=t) one-tail	0,171		0,000		0,088	
Critical value of t (one-tail)	1,666		1,678		1,670	
P(T<=t) two-tail	0,342		0,0001		0,176	
Critical value of t (two-tail)	1,993		2,012		1,999	
Alpha: 0.05	Medium			Low		
	Age		Time of Diagnosis		BMI	
Means	62,551	55,667	6,971	8,667	30,368	30,291
Variances	117,919	101,333	34,033	36,333	22,510	140,578
Statistical t	1,144		-0,474		0,011	
P(T<=t) one-tail	0,185		0,341		0,496	
Critical value of t (one-tail)	2,920		2,920		2,920	
P(T<=t) two-tail	0,371		0,682		0,992	
Critical value of t (two-tail)	4,303		4,303		4,303	

Table 5.3: Statistical t for age, time of diagnosis and body mass index (BMI) using the by-disease classification

	By-disease classification					
Alpha: 0.05	**Healthy**			**Neuropathy**		
	Age		**Time of Diagnosis**		**BMI**	
Means	58,200	61,841	4,017	9,151	28,488	29,762
Variances	70,700	96,071	9,335	43,393	34,033	27,215
Statistical t	-0,920		-3,212		-0,474	
P(T<=t) one-tail	0,200		0,007		0,328	
Critical value of t (one-tail)	2,015		1,895		2,015	
P(T<=t) two-tail	0,400		0,015		0,656	
Critical value of t (two-tail)	2,571		2,365		2,571	
Alpha: 0.05	**Healthy**			**Mixed**		
	Age		**Time of Diagnosis**		**BMI**	
Means	58,200	69,588	4,017	15,858	28,488	30,040
Variances	70,700	136,507	9,335	159,021	34,033	33,994
Statistical t	-2,419		-3,535		-0,523	
P(T<=t) one-tail	0,019		0,001		0,309	
Critical value of t (one-tail)	1,833		1,725		1,895	
P(T<=t) two-tail	0,039		0,002		0,617	
Critical value of t (two-tail)	2,262		2,086		2,365	
Alpha: 0.05	**Mixed**			**Neuropathy**		
	Age		**Time of Diagnosis**		**BMI**	
Means	69,588	61,841	15,858	9,151	30,040	29,762
Variances	136,507	96,071	159,021	43,393	33,994	27,215
Statistical t	2,506		2,116		0,178	
P(T<=t) one-tail	0,010		0,024		0,430	
Critical value of t (one-tail)	1,717		1,734		1,714	
P(T<=t) two-tail	0,020		0,049		0,860	
Critical value of t (two-tail)	2,074		2,101		2,069	

Table 5.3 shows that the age (t=2.506) and the time of diagnosis (t=2.116) are different in the Neuropathy (61.8 and 9.1 years respectively) compared to the Mixed group (69.5 and 15.8 years). This means that the age and time of diagnosis are important features regarding the by-disease classification. Time of diagnosis is also different from Healthy to Neuropathy (t=-3.212), and also from Heatthy to Mixed (t=-3.535). This time is about 4, 9, and 16 years for repectivelly Healthy, Neuropathy, and Mixed.

Tables 5.4 and 5.5 show the |ΔT°|, ML, MR, SL and SR parameters using the two classifications.

Table 5.4: Statistical t for |ΔT°|, ML, MR, SL and SR using the by-risk classification

By-risk classification					
Alpha: 0.05	**High**			**Low**	
	|ΔT°|	**ML**	**MR**	**SL**	**SR**
Mean	0,528 0,439	31,832 32,083	31,728 31,824	0,635 0,642	0,617 0,687
Variance	0,059 0,031	2,736 0,080	3,102 0,217	0,039 0,007	0,040 0,006
Statistical t	0,802	-0,758	-0,237	-0,122	-1,259
P(T<=t) one-tail	0,241	0,228	0,409	0,454	0,132
Critical value of t (one-tail)	2,353	1,721	1,812	2,132	2,015
P(T<=t) two-tail	0,481	0,457	0,817	0,909	0,264
Critical value of t (two-tail)	3,182	2,080	2,228	2,776	2,571
Alpha: 0.05	**High**			**Medium**	
	|ΔT°|	**ML**	**MR**	**SL**	**SR**
Mean	0,528 0,568	31,832 30,979	31,728 30,911	0,635 0,675	0,617 0,639
Variance	0,059 0,072	2,736 4,140	3,102 4,653	0,039 0,036	0,040 0,023
Statistical t	-0,697	2,086	1,878	-0,906	-0,551
P(T<=t) one-tail	0,244	0,020	0,032	0,184	0,292
Critical value of t (one-tail)	1,666	1,665	1,665	1,668	1,673
P(T<=t) two-tail	0,488	0,040	0,064	0,368	0,584
Critical value of t (two-tail)	1,993	1,991	1,991	1,996	2,003
Alpha: 0.05	**Medium**			**Low**	
	|ΔT°|	**ML**	**MR**	**SL**	**SR**
Mean	0,568 0,439	30,979 32,083	30,911 31,824	0,675 0,642	0,639 0,687
Variance	0,072 0,031	4,140 0,080	4,653 0,217	0,036 0,007	0,023 0,006
Statistical t	1,178	-3,312	-2,232	0,571	-0,980
P(T<=t) one-tail	0,162	0,001	0,025	0,304	0,200
Critical value of t (one-tail)	2,353	1,711	1,812	2,353	2,353
P(T<=t) two-tail	0,324	0,003	0,050	0,608	0,399
Critical value of t (two-tail)	3,182	2,064	2,228	3,182	3,182

Mean temperature is different from Low to Medium, and from Medium to High. But there is no difference between Low and High groups.

For the Low group, the mean temperature is around 32°C. For the medium group, it goes down to 31°C, and increases for High risk to a value close to 32°C.

If this result is confirmed by other clinical tests, it may be of a great help for the early diagnosis of diabetic foot: in the early stage, *i.e.* from the Low risk to Medium risk, the plantar foot surface temperature is lowered by 1°C.

Table 5.5: Statistical t for $|\Delta T°|$, ML, MR, SL and SR using the by-disease classification

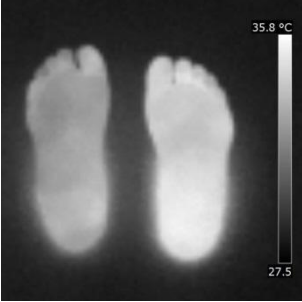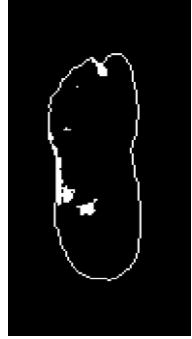|	By-disease classification				
Alpha: 0.05	Healthy			Neuropathy	
	$\mathbf{|\Delta T°|}$	ML	MR	SL	SR
Mean	0,516 0,528	29,559 31,514	29,394 31,477	0,643 0,672	0,695 0,640
Variance	0,034 0,067	6,335 3,615	7,226 3,910	0,037 0,037	0,018 0,029
Statistical t	-0,135	-1,699	-1,696	-0,331	0,855
P(T<=t) one-tail	0,449	0,082	0,083	0,377	0,216
Critical value of t (one-tail)	2,015	2,132	2,132	2,015	2,015
P(T<=t) two-tail	0,898	0,165	0,165	0,754	0,431
Critical value of t (two-tail)	2,571	2,776	2,776	2,571	2,571
Alpha: 0.05	Healthy			Mixed	
	$\mathbf{|\Delta T°|}$	ML	MR	SL	SR
Mean	0,516 0,629	29,559 31,264	29,394 31,008	0,643 0,610	0,695 0,586
Variance	0,034 0,063	6,335 2,194	7,226 2,775	0,037 0,035	0,018 0,032
Statistical t	-1,094	-1,443	-1,273	0,341	1,467
P(T<=t) one-tail	0,151	0,104	0,130	0,372	0,088
Critical value of t (one-tail)	1,833	2,015	2,015	1,943	1,833
P(T<=t) two-tail	0,302	0,209	0,259	0,744	0,176
Critical value of t (two-tail)	2,262	2,571	2,571	2,447	2,262
Alpha: 0.05	Neuropathy			Mixed	
	$\mathbf{|\Delta T°|}$	ML	MR	SL	SR
Mean	0,528 0,629	31,514 31,264	31,477 31,008	0,672 0,610	0,640 0,586
Variance	0,067 0,063	3,615 2,194	3,910 2,775	0,037 0,035	0,029 0,032
Statistical t	-1,453	0,580	0,988	1,220	1,124
P(T<=t) one-tail	0,079	0,283	0,166	0,117	0,136
Critical value of t (one-tail)	1,706	1,694	1,699	1,706	1,711
P(T<=t) two-tail	0,158	0,566	0,332	0,233	0,272
Critical value of t (two-tail)	2,056	2,037	2,045	2,056	2,064

No difference is found between the groups of the by-disease classification.

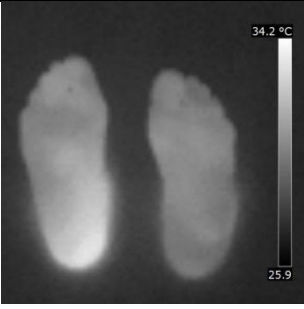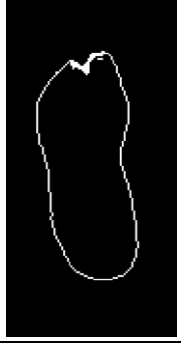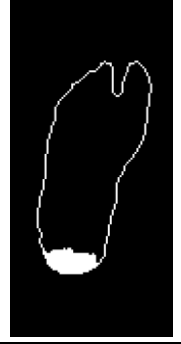## 5.2.3. Foot temperature difference analysis
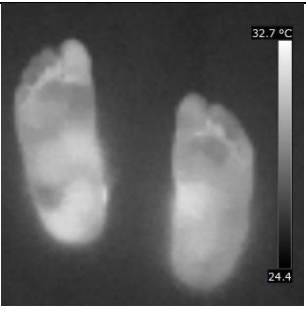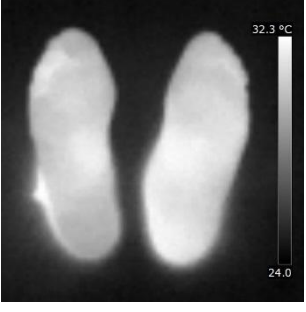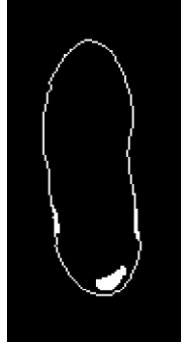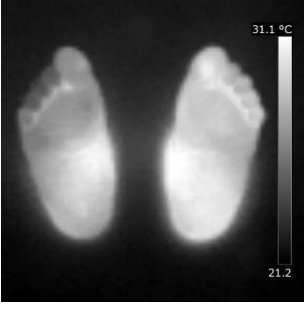
We now focus on the analysis of the point to point absolute difference between the right foot and the left foot named $|\Delta T°|$. Values of $|\Delta T°|$ greater than 2.2°C are of interest. Remember that this upper limit can be an early sign of ulcer. The percentage of such points are called %.

When % is greater than 1%, it roughly corresponds to a surface of 1 cm of diameter. It is also the smallest area at risk for the foot seen in Figure 2.4. This limit was therefore chosen. This analysis points out region with significative hyperthermia.

9 images out of the 85 images of the database have a percentage greater than 1%. These 9 images are presented in Figure 5.1. The right column shows the contours and pixels such that $|\Delta T°|$ is greater than 2.2°C.

Original image	Difference image	Contours and hyperthermia
	IR_695	
Original image	Difference image	Contours and hyperthermia
	IR_700	

Original image	Difference image	Contours and hyperthermia
	IR_709	
Original image	Difference image	Contours and hyperthermia
	IR_734	
Original image	Difference image	Contours and hyperthermia
	IR_797	
Original image	Difference image	Contours and hyperthermia
	IR_896	

Original image	Difference image	Contours and hyperthermia
	IR_972	
Original image	Difference image	Contours and hyperthermia
	IR_981	
Original image	Difference image	Contours and hyperthermia
	IR_992	

Figure 5.1: The original 9 images with % greater than 1%, the corresponding difference image, and their contours and hyperthermia regions

Images 709, 896, 972, and 981 show hyperthermia in the heeling region. Images 734, 797, and 992 reveal toes hyperthermia. The two other images 695 and 700 show a other kind of hyperthermia.

6 persons are from the Medium risk group, and 3 from the High risk group. The highest percentage was found to be 18% for image 992. One can see a segmentation problem in the toes region.

In this clinical trial, 10% of people having a regular exam in a hospital present a significative hyperthermia of the plantar foot. In the domain of foot ulcer analysis, it is the first time to our knowledge that a precise analysis of hyperthermia regions is available for medical doctors. This indication may be of a substantial help because it allows detecting significant hyperthermia areas with a temperature difference greater than 2.2°C, early signs of foot ulcers.

5.3 Discussion

The overall object of the project was to develop new strategies to improve the early diagnosis of type 2 diabetic foot from the analysis of thermal images.

Even if the number of Low risk persons involved in this medical study was too little (only 3) to be significant, this population can be considered in this discussion. It was found that the mean temperature is decreasing of 1°C from Low to Medium risk patients, and increasing from Medium to High risk persons by 1°C. The main interest regarding our goals is that the mean temperature of the plantar foot surface decreases from Low to Medium risk persons and can be an early sign of diabetes.

The Healthy population was also too small in numbers (only 5 persons). But here no temperature indicator was significantly different between the Healthy group and the two other groups (Neuropathy, and Mixed). Two other groups would have been interesting in the medical study conducted during the Thesis:

- An Ischemia group in the by-disease classification. Unfortunately no such persons were found.
- A Control group corresponding to persons without type 2 diabetes (and of course without diabetic foot).

No doubt that new medical studies will be conducted where a significant number of persons with a difficult diagnosis of diabetic foot will be included: Low risk, and Healthy. In addition, Ishemia and Controls will be considered too.

For a Control person (no type 2 diabetes), the temperature distribution in the plantar foot is not uniform and shows what is called a bilateral butterfly pattern [Chan, 1991]. In addition, plantar foot temperature varies in diabetic foot due to thermoregulation problems related to neuropathy and/or ischemia, and also in case of inflammation. The standard deviation was expected to reveal these different variations. However, no differences, whatever the type of

classification between the groups, were found. Instead of the standard deviation, a region analysis as the one proposed in Figure 3.9 by [Sun et al., 2006] could be of interest.

Temperature of corresponding area of the right and left feet do not usually differs more than 1°C in diabetic foot. A temperature difference $|\Delta T°|$ greater than 2.2°C is considered as abnormal. Points such that $|\Delta T°|$ is greater than 2.2°C are of interest. 9 persons such that this percentage of points was greater than 1% (the surface of the smallest area at risk) were found out of 85. It means that around 10% of type 2 persons coming in the hospital for an ordinary consultation in the diabetes service have a significant region of hyperthermia. It would be interesting to know if this analysis could help a medical doctor in Hospital.

5.4. Conclusion

A transversal clinical study was conducted including a population of type 2 diabetes before a possible ulceration occurs. 85 such exams were performed from 1 February to 30 June 2013 in the Dos de Mayo hospital.

The patients were first all examined by the same medical doctor who realized the by-risk and by-disease classification: 33 were High risk, 49 Medium risk, and 3 Low risk. In addition, 17 were Mixed (neuropathy + ischemia), 63 were Neuropathy, and 5 were Healthy.
A Student's t-test was performed regarding age, time of diagnosis, and body mass index. Age and time of diagnosis were different in the Medium risk and High risk groups. It was also different in the Neuropathy group compared to the Mixed group (neuropathy + ischemia). This means that the age and time of diagnosis are important features regarding both classifications.

The thermal image was acquired using the same chosen IR camera and in accordance to the robust acquisition protocol. The image was analyzed by the automatic image processing software. Student's t-tests were performed for $|\Delta T°|$, ML, MR, SL and SR using the by-risk classification. From the Low risk to Medium risk, the plantar foot surface is lowered by 1°C. This result could be of a high interest for the early diagnosis of diabetic foot. It should be confirm by other clinical studies involving more Low risk patients.

For the by-disease classification, no difference was found for $|\Delta T°|$, ML, MR, SL and SR.

It was finally focused on the values of the points such that $|\Delta T°|$ is greater than 2.2°C. 9 images out of the 85 images of the database had a percentage greater than 1%. This analysis clearly points out hyperthermia regions and may be of a substantial help in the early prevention of ulcers in hospital.

5.5 Etude médicale (in french language)

Le but global du projet est de trouver de nouvelles stratégies pour améliorer le diagnostic précoce du pied diabétique à partir de l'analyse d'images thermiques. Ainsi une étude clinique transversale a été menée sur une population de personnes diabétiques de type 2 avant qu'une ulcération possible ne se produise.

L'Hôpital National Dos de Mayo (HNDM) à Lima , Pérou, a autorisé la réalisation de cette étude et tous les patients ont donné leur consentement écrit. Des critères d'inclusion, d'exclusion ou de retrait de patients ont été définis pour cette étude médicale afin d'éviter tout problème dans la gestion des résultats obtenus avec le traitement des images thermiques.

Des personnels expérimentés de l'hôpital ont pris en charge les patients diabétiques et ont recueilli de nombreuses informations qui ont permis, en autre, de classifier les patients de deux manières différentes : par risque (faible, moyen ou élevé) ou par maladie (sain, ischémie, neuropathie ou mixte). L'examen médical de chaque patient durait environ 30 minutes : 15 minutes pour l'équilibre thermique requis dans le protocole d'acquisition puis 15 minutes pour l'installation du patient et l'acquisition de l'image thermique de la voute plantaire des pieds.

85 examens ont été effectués à partir du 1er février jusqu'au 30 juin 2013 à l'hôpital Dos de Mayo. Même si le protocole standardisé a été appliqué, il a été constaté que la variabilité est grande dans les formes, les orientations, les textures et les contours des pieds qui appartiennent à cette base de données.

Pour être statistiquement significatif, un groupe doit être au moins composé de 30 personnes. Dans le classement par risque, le nombre de patients à faible risque est trop petit (seulement 3). L'analyse statistique de cette population est à prendre avec le plus grand soin. Dans le classement par maladie, aucun patient ne souffrait que d'ischémie. En outre, le nombre de patients classés "mixte" est faible et le nombre de patients sains est trop petit (5 uniquement).

Pour évaluer si une différence apparaît entre ces différents groupes, le test de Student est réalisé avec un niveau de signification α = 0,05 sur l'âge, le moment du diagnostic de la maladie et l'IMC.
Dans le classement par risque, seul le moment du diagnostic de la maladie entre la population "risque moyen" et "haut risque" est différent entre les deux groupes. Cela signifie que le moment du diagnostic est un élément important en ce qui concerne la classification par risque. De la même manière, dans le classement par maladie, il ressort que l'âge et le moment du diagnostic sont des éléments importants permettant de dissocier les patients souffrant de

neuropathie de ceux souffrant à la fois de neuropathie et d'ischémie. C'est également le cas du critère "moment du diagnostic" entre les patients sains et neuropathiques, tout comme entre les patients sains et mixtes.

Le test de Student a également été appliqué sur les paramètres de la moyenne de la différence de température entre les 2 pieds, la moyenne de température de chaque pied ainsi que l'écart type. Pour la classification par risque, nous observons que la température moyenne des pieds est différente entre les patients "faible risque" et "haut risque", mais aussi entre les patients "risque moyen" et "haut risque". Si ce résultat est confirmé par d'autres essais cliniques, il peut être d'une grande aide pour le diagnostic précoce du pied diabétique. Par contre, aucune différence n'est observée entre les groupes de la classification par maladie.
Il faut noter que l'écart-type devait révéler des variations de température dans le pied diabétique en raison de problèmes de thermorégulation liés à la neuropathie et/ou l'ischémie, et aussi en cas d'inflammation. Cependant, aucune différence, quel que soit le type de classification entre les groupes, n'a été trouvée. Plutôt que de travailler sur le pied dans sa globalité, il semblerait qu'une analyse par régions du pied fournirait de meilleurs résultats.

L'analyse de la différence absolue point à point de la température entre le pied droit et le pied gauche est un autre point essentiel de ce projet : les valeurs de $|\Delta T°|$ supérieures à 2,2 °C peuvent être un signe précoce de l'ulcère du pied. Le pourcentage de ces points est également pris en considération. 9 patients ont ainsi été détectés comme souffrant d'hyperthermie significative au niveau de la voûte plantaire : 6 personnes appartiennent au groupe "risque moyen" et 3 au groupe "haut risque". Dans le domaine de l'analyse de l'ulcère du pied, c'est la première fois, à notre connaissance, qu'une analyse précise des régions de l'hyperthermie est disponible pour les médecins. Cette indication peut être d'une aide importante car elle permet de détecter les zones d'hyperthermie significative, les premiers signes d'ulcère du pied.

Nul doute que de nouvelles études médicales devront être menées, incluant un nombre bien plus important de patients "faible risque" et sains, mais aussi un groupe de patients souffrant uniquement d'ischémie et un groupe de contrôle correspondant à des personnes non diabétiques de type 2 (et bien sûr sans pied diabétique).

CHAPTER VI

6. Conclusions and perspectives

CONCLUSIONS

Diabetic foot is a major public health problem. The aim of this project was to analyse the potential of thermography in the early diagnosis of type 2 diabetic foot in hospitals. Main advantages of thermography are that it is simple to use, non-invasive, contactless, non-irradiant, and fast.

In chapter 2, diabetes and its related complications were considered. The strategy of diabetic foot diagnosis used in the Dos de Mayo Hospital in Lima was studied. This lead us to the definition of the object of the present thesis.

In chapter 3, industrial applications of thermography were presented, followed by the one related in medicine. The potential of thermography in this domain are of importance. The main research works in thermography for diabetic foot disorders were discussed: thermography can help in the diagnosis of diabetic foot, and can reduce the incidence of foot ulcer. The last section of this chapter was the selection of the thermal camera: the FLIR i5 model was chosen.

In the following chapter, we were able to propose an acquisition protocol to ensure a high reproducibility of the results. To our knowledge, this protocol is new in the domain and insures a high quality of thermal foot images. The thermal image of the plantar foot is a light region surrounded by a homogeneous black background.
An automatic and novel image processing method was proposed. It was composed of three steps: preprocessing, segmentation, and finally registration. From these steps, various parameters can be assessed: the mean and standard deviation of the plantar foot surface of right and left feet (MR, ML, SR, and SL respectively) as well as $|\Delta T°|$, the point to point absolute difference temperature between right and left feet.

A transversal clinical study was including a population of type 2 diabetes before a possible ulceration occurs. 85 such exams were performed in the Dos de Mayo hospital. The patients were first all examined by the same medical doctor. They were asked to give their age, the time of diagnosis, and their body mass index. Following this, the medical doctor made the medical assessment, and the by-risk and by-disease classifications: 33 were High risk, 49 Medium risk, and 3 Low risk. In addition 17 were Mixed (neuropathy + ischemia), 63 were Neuropathy, and 5 Healthy.

A Student's t-test was performed regarding age, time of diagnosis, and body mass index. Age and time of diagnosis were different in the Medium and High risk group. It was also different in the Neuropathy compared to the Mixed group (neuropathy + ischemia). This means that the age and time of diagnosis are important features regarding both classifications.

Images were acquired using the defined acquisition protocol, and analysed with our automatic software. From this analysis, the chosen parameters were assessed: $|\Delta T°|$, MR, ML, SR, and SL.

Student t-tests were performed using the by-risk classification. For the Low risk group, the mean temperature is around 32°C. For the Medium risk group, it goes down to 31°C, and increases for the High risk group to a value of 32°C. In the early stage, *i.e.* from the Low risk group to Medium risk group, the plantar foot surface is lowered by 1°C. If this result is confirmed by other clinical tests, it may be of a great help for the early diagnosis of diabetic foot.

At the opposite, no difference was found between the groups in the by-disease classification.

It was then focused on the values of the percentage of points such that $|\Delta T°|$ is greater than 2.2°C. 9 images out of the 85 images of the database have a percentage greater than 1%. This clinical trial demonstrates that 10% of people having a regular exam in a hospital present a significative hyperthermia of the plantar foot. Showing to the medical doctor these regions may be of a substantial help in the early prevention of an ulcer in hospital.

PERSPECTIVES

Short term, medium term and long term projects will be further developed.

Short term projects
The first one is related to the assessment of the reproducibility. The intra-observer, inter-observer, and long term reproducibilities will be measured.

The second project concerns the enlargement of the database. The by-risk classification includes Low risk, Medium risk, and High risk groups. The by-disease classification is

composed of Healthy (no ischemia or neuropathy), Ischemia, Neuropathy, and Mixed (ischemia + neuropathy) groups. In the medical study, the Low risk group as well as the Healthy group were too small. These groups are of high interest because the diagnosis of diabetes is difficult for them. Moreover, the Ischemia group was not present. No doubt that new medical studies will be conducted where such persons (Low risk, Healthy, and Iscemia) will be of interest (includind Controls for comparison).

Medium terms projects

At first, it concerns the improvement of the image processing software. The software is expected to be more robust regarding possible acquisition problems that occur mainly in the toes region, or in the malleolus area.

The polyurethane foam makes that positioning a patient for the image acquisition is long and potentially difficult in some cases, especially for old persons. It is expected to develop an image processing method that could be operational when no polyurethane foam is present. It that case, the background will not be homogeneous so that the segmentation will be a difficult issue.

As seen in the various images, the texture of the plantar foot surface is different from one image to the other. A texture analysis may be of interest. Indicators of the surface texture will be developped as for example fractal parameters.

The temperature distribution in the plantar foot varies from a bilateral butterfly pattern for controls to more complicated shapes for type 2 diabetes. A region analysis as the one proposed in Figure 3.9 by [Sun et al., 2006] could be of interest to assess these temperature distributions.

Long term projects

Recently, the University of Orléans and the Universidad Federal Fluminense of Rio de Janeiro have asked for a financial support by answering to a call for project from CAPES-Cofecub. The subject concerns the breast cancer analyzed by thermal images. It also involves the Orléans hospital as well as the Antonio Pedro de Rio hospital of Rio de Janeiro.

These two projects (foot ulcer and breast cancer) will possibly interact and will lead to the creation of an international network devoted to the development of thermal images in medicine.

Conclusions et perspectives (in french language)

CONCLUSIONS

Le pied diabétique est un problème majeur de santé publique. Le but de ce projet était d'analyser le potentiel de la thermographie dans le diagnostic précoce de pieds diabétiques, diagnostic effectué dans les hôpitaux. Les principaux avantages de la thermographie sont qu'elle est simple à utiliser, non invasive, sans contact, non irradiante et rapide.

Dans le chapitre 2, le diabète et ses complications ont été présentés. La stratégie de diagnostic du pied diabétique utilisé à l'hôpital Dos de Mayo à Lima a été étudiée. Ceci nous conduit à la définition de l'objctif de la présente thèse.

Dans le chapitre 3, les applications industrielles de thermographie ont été décrites, suivi par celles concernant la médecine. Le potentiel de la thermographie dans ce domaine est d'une importance considérable. Les principaux travaux de recherche dans la thermographie pour les troubles du pied diabétique ont été abordées : la thermographie peut aider dans le diagnostic du pied diabétique, et peut réduire l'incidence de l'ulcère du pied . La dernière section de ce chapitre a été le choix de la caméra thermique : le modèle FLIR i5 a été retenu.

Dans le chapitre suivant, nous avons décrit un protocole d' acquisition qui permet d'assurer une bonne reproductibilité des résultats. A notre connaissance, ce protocole est nouveau dans le domaine et assure une haute qualité d'images du pied. L'image thermique de la voute plantaire est alors une région claire entourée par un fond noir homogène. La procédure automatique de traitement d'image est composée de trois étapes : prétraitement, segmentation, et enfin recallage. De ces étapes, différents paramètres peuvent être évalués : la moyenne et l'écart de la surface plantaire du pied droit et gauche (MR, ML, SR et SL, respectivement), ainsi que $|\Delta T°|$, la différence absolue point à point de la température entre le pied droit et gauche, ainsi que le pourcentage de pixels tels que la différence de température entre le pied droit et gauche est supérieure à 2,2°C. Un tel pourcentage supérieur à 1% indique les régions en hyperthermie.

Une étude clinique a concerné une population de diabétiques de type 2. 85 de ces examens ont été effectués à l'hôpital Dos de Mayo à Lima, Pérou. Les patients ont d'abord été tous examinés par le même médecin. Ils ont été invités à donner leur âge, le moment du diagnostic de leur dièbete, et leur indice de masse corporelle. Suite à cela, le médecin a fait l'évaluation médicale et les a classé : 33 étaient à Risque élevé, 49 à Risque moyen, et 3 à Risque faible.

Le Test t de Student a été réalisé en ce qui concerne l'âge, le moment du diagnostic, et l'indice de masse corporelle. L'âge et le moment du diagnostic étaient différentes entre le groupe Risque moyen et le groupe à haut Risque. Cela signifie que l'âge et le moment du diagnostic sont des caractéristiques importantes.

Les images ont été acquises en utilisant le protocole d'acquisition défini et analysées avec notre logiciel automatique. A partir de cette analyse, les paramètres retenus ont été évalués : $|\Delta T°|$, MR, ML, SR et SL.

Les Test t de Student ont été effectuées en utilisant la classification par risque. Pour le groupe à faible Risque, la température moyenne se situe autour de 32°C. Pour le groupe de Risque

moyen, elle descend à 31°C et eugmente pour le groupe à haut Risque à une valeur proche de 32°C. Au stade précoce, c'est à dire entre le groupe à faible Risque et le groupe à Risque moyen, la surface plantaire est abaissée de 1 ° C. Si ce résultat est confirmé par d'autres essais cliniques, il peut être d'une grande aide pour le diagnostic précoce du pied diabétique. Nous avons alors analysé le pourcentage de points tels que |AT°| est supérieur à 2,2 ° C. 9 images sur les 85 images de la base ont un tel pourcentage supérieur à 1 %. Cet essai clinique démontre que 10% des personnes ayant un examen régulier dans un hôpital présentent une hyperthermie significative de la voute plantaire. Donner cette information au médecin peut être d'une aide considérable dans la prévention précoce d'un ulcère.

PERSPECTIVES

Des projets à court terme, moyen terme et des projets à long terme seront développés.

Projets à court terme
La premier est lié à l'évaluation de la reproductibilité. Les reproductibilités intra-observateur, inter- observateur et la reproductibilité à long terme seront mesurées.
Le second projet concerne l'élargissement de la base de données. La classification par risque comprend les Risque faible, moyen, et le groupe à haut Risque. La classification par maladie se compose de personnes saines (absence d'ischémie et neuropathie), le groupe ischémie, le groupe neuropathie, et enfin le groupe mixte (ischémie + neuropathie). Dans l'étude médicale, le groupe de Risque faible ainsi que le groupe en bonne santé étaient trop petits. Ces groupes sont d'un grand intérêt car le diagnostic du diabète est difficile pour eux. Par ailleurs, le groupe ischémie n'était pas présent. Nul doute que de nouvelles études médicales seront effectuées dans lesquelles ces personnes (Risque faible, en bonne santé, et ischémie) seront d'intérêt.

Projets à moyen terme
Dans un premier temps, il s'agit d'améliorer le logiciel de traitement d'images. On prévoit que le logiciel sera plus robuste en ce qui concerne les problèmes d'acquisition possibles qui se produisent principalement dans la région des orteils, ou dans la zone de la malléole.
La mousse de polyuréthane fait que le positionnement d'un patient pour l'acquisition de l'image est long et potentiellement difficile dans certains cas, notamment pour les personnes âgées. Il est prévu de mettre au point un procédé de traitement d'image pouvant être opérationnel en l'absence de la mousse de polyuréthane. Dans ce cas, le fond ne sera pas homogène et la segmentation automatique sera difficile.
Comme on le voit dans les différentes images, la texture de la surface du pied est différente d'une image à l'autre. Une analyse de la texture peut être intéressante. Des indicateurs de l'état de surface seront développés comme par exemple des paramètres fractals.
La répartition de la température de la voute plantaire varie depuis une forme en papillon pour les personnes saines à des formes plus complexes pour des diabètiques de type 2. Une analyse

par région comme celle qui est proposée dans la figure 3.9 par [Sun et al., 2006] pourrait être intéressante pour étudier plus finement ces distributions de température.

Les projets à long terme

Récemment, l'Université d'Orléans et l'Université fédérale Fluminense de Rio de Janeiro ont demandé une aide financière en répondant à un appel à projet CAPES-Cofecub. Le sujet concerne le cancer du sein analysé par des images thermiques. Il implique également l'hôpital d'Orléans ainsi que l'hôpital Antonio Pedro de Rio de Rio de Janeiro. Ces deux projets (ulcère du pied et cancer du sein) pourront interagir et ceci mènera à la création d'un réseau international consacré au développement des images thermiques en médecine.

CHAPTER	**VII**

7. Appendixes

Appendix A: Thermal image sensor technology

Appendix B: Agreement

Appendix C: The 85 images of the medical study

Appendix D: Parameters of the 85 images of the medical study

Appendix A: Thermal image sensor technology

An infrared detector is a detector that reacts to infrared (IR) radiations. The two main types of detectors are thermal and photonic (photodetectors). The thermal effects of the incident IR radiation can be followed through many temperature dependent phenomena. Bolometers and microbolometers are based on changes in resistance. They are used in most today thermal camera.

Microbolometer Technology: Basic Principle of Thermal Detection
The recent advances in microelectromechanical systems (MEMS) technology allow fabricating sensitive thermal bolometric detectors on thermally isolated hanging membranes. A bolometer employs a characteristic of thermally sensitive layer that changes its sheet resistance according to the change of the temperature (the larger the resistance change, the higher the temperature coefficient of resistance (TCR), so, higher of sensitivity). Many materials have been used for IR active layer of bolometer such as metals (Au, Pt, Ti, etc.) and semiconductors (VOx, amorphous silicon, etc). The main thrust is to develop a technology that provides ultra low cost thermal IR imagers.

A bolometer measures the changes in the heat input from the surroundings and converts this into a measurable quantity such as a voltage or current. A bolometer therefore typically consists of an absorber and a thermometer, resulting in the increase in temperature due to absorption of IR radiations that ultimately causes a change in resistance of bolometer elements. The resistance change information is electrically transferred to the read-out integrated circuit (ROIC) for further processing. To obtain high sensitivity, the thermometer is kept thermally insulated with the ROIC substrate. The schematic block diagram of a typical microbolometer detector structure is illustrated in Fig. 1.

The analysis of thermal IR detectors begins by solving the heat flow equation that describes the temperature increase in terms of the incident radiant power. The heat flow equation describing the pixel is:

$$C\frac{d(\Delta T)}{dt} + G(\Delta T) = \eta P = \eta Po(\exp{(j\omega t)}) \qquad (1)$$
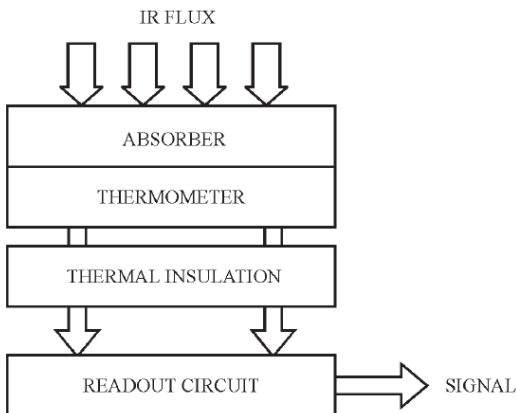
Figure 1: Schematic block diagram of a thermal detector (microbolometer) [Bhan,2009]

where, C is heat capacity of the sensitive area of a pixel; G is thermal conductance of the support structure; P_O is amplitude of modulated IR radiation power falling on pixel; η is absorbance of IR sensitive films; ω is angular frequency of

modulation of the radiation; and $\Delta T°$ is temperature increase of the sensitive area of the pixel. This simplified equation assumes that the power dissipation in the sensitive area due to applied electrical bias can be neglected. The solution of Eqn (1) is:

$$\Delta T = \frac{\eta Po(\exp{(j\omega t)})}{G+j\omega C} = \frac{\eta Po}{G(1+\omega^2\tau^2)^{1/2}} \tag{2}$$

where, τ is the thermal response time. The temperature measurement is simplified when the resistance possesses a linear temperature dependence that holds true for most metals. For such a material, the resistance R can be expressed as:

$$R = Ro\{1+\alpha(T-To)\} \tag{3}$$

where, R_O is the resistance at the temperature T_O and α is the temperature coefficient of resistance (TCR). The temperature increase, $\Delta T = T-T_o$, due to the absorption of IR radiation is small enough so that the resistance change ΔR is linear with ΔT., i.e.,

$$\text{or } \Delta R \, \alpha \, \Delta T° \tag{4}$$
$$\Delta R = \alpha \, R \, \Delta T° \tag{5}$$
$$\text{where, } \alpha = (1/R) \, dR/dt \tag{6}$$

The responsivity R_v of an IR pixel is defined as the output signal (voltage or current) divided by the input radiant power falling on the pixel. Let the output signal be the voltage V_s, then:

$$V_s = I_b \, \Delta R = I_b \, \alpha \, R \, \Delta T° \tag{7}$$

where, I_b is the bias current through the pixel. From Eqns (2) and (7), one gets:

$$Vs = \frac{\eta Po I_b \alpha}{G(1+\omega^2\tau^2)^{1/2}} \tag{8}$$

The responsivity (Rv) is defined by the following relation.

$$R_v = V_S / P_O \tag{9}$$

Hence,

$$Rv = \frac{\eta I_b \alpha}{G(1+\omega^2\tau^2)^{1/2}} \tag{10}$$

Equation (10) shows that the responsivity is directly proportional to the temperature coefficient of resistance (α) and inversely proportional to the thermal conductance (G) associated with the principal heat loss mechanism. Both parameters are important for uncooled IR resistive bolometers. The value of G can range over several orders of magnitude, whereas the range of possible values of α is far less. The primary focus should be on the thermal isolation structure. The choice of resistive material is also an important parameter and should be a secondary consideration. It should be compatible to the processing of sensor. Equation (2) is basic to thermal IR arrays. It describes the temperature increase of the resistive area of the pixel when radiation of power amplitude P_o sinusoidally modulated with angular frequency ω falls on the sensitive area. The pixel temperature increases and decreases as the input radiant power rises and falls in an oscillatory manner. The transition between the low and high frequency regions is characterized by the thermal time constant τ or thermal response time, that is defined as:

$$\tau = C/G \tag{11}$$

Another important parameter of thermal IR detector is detectivity D and is given by

$$D = (R_v A \Delta f)/V_n \tag{12}$$

where, Δf is the detector noise bandwidth (Hz), V_n is the total detector noise, and A is the detector area.

The important measure of the performance of IR imaging system is noise equivalent temperature difference (NETD) that is the difference in the temperatures of objects in a scene, which will produce a signal-to-noise ratio of 1. It is given by:

$$\text{NETD} = \frac{4F^2 V_n}{(\Delta P/\Delta T)\tau_o A R_v} \tag{13}$$

where, F is the focal ratio of the optics and τ_o, is the transmittance of the optics, $(\Delta P/\Delta T)_{\lambda 1-\lambda 2}$ is the change in power per unit area radiated by scene (or blackbody) at temperature T, and T is measured within the spectral band from $\lambda_1-\lambda_2$. Smaller NETD indicates better performance.

Appendix B: Agreement

1. **Título: Determinación de la capacidad de predicción diagnóstica de lesiones finales en Pie Diabético a partir de exámenes periódicos de termografía**.
2. **Autor y Coautores**: Lic. María Teresa Arista Rivera HNDM, MSc. Ing. Luis Alberto Vilcahuamán Cajacuri PUCP, Dr. Hugo Cesar Arbañil Huamán HNDM, MSc. Ing. José Ferrer PUCP.

3. **Introducción**:

   a. **Formulación del Problema:**

Es posible el diagnóstico temprano de lesiones finales en pie diabético a partir del análisis de imágenes térmicas? Las complicaciones de pie diabético están asociadas a los altos costos y a la baja calidad de vida de los pacientes. Se estima que en la actualidad hay en el Perú más de un millón de personas que padecen diabetes. Esta sub-población tiene un impacto socioeconómico importante para el país debido a que el segmento de dicha sub-población que no es atendido pueden terminar desarrollando severas complicaciones como el Pie Diabético que producen discapacidad o desenlaces fatales. De otro lado el segmento que es atendido tardíamente, incrementa la demanda de servicios ambulatorios y de hospitalización prolongada. El diagnóstico precoz o despistaje y el monitoreo preventivo que permita evitar llegar al estado de Pie Diabético se hace relevante si se realiza de forma sistemática (rápida) y no-invasiva para la atención de una población considerable. Consideramos lesiones finales a la gangrena seca y las ulceraciones.

   b. **Justificación:**

Fisiológicas: Aproximadamente el 40% de los pacientes que padecen diabetes desarrollan neuropatías y angiopatías de las extremidades inferiores, estas son complicaciones adicionales que incrementa la demanda por servicios de salud especializados y los costos asociados. Un enfoque preventivo como la que permite la termografía ayudaría a reducir este efecto.

Morbilidad: La diabetes es una enfermedad crónica de larga duración que requiere alto cuidado y prevención de complicaciones muchas veces irreversibles. Se estima que más de 400,000 personas en el Perú tienen en la actualidad riesgo de padecer complicaciones del pie diabético. Estas complicaciones reducen dramáticamente la calidad de vida de los pacientes y sus familiares. La termografía sería un medio para evitar estos riesgos en los pacientes.

Tratamiento limitado: La medicina considera a las complicaciones de la diabetes patologías de difícil curación debido a las limitaciones de aplicación de fármacos en pacientes muy debilitados en su sistema digestivo y piel. Por ello es muy importante detectar, tratar y prevenir de forma precoz toda complicación. Un medio alternativo es la termografía de la planta del pie.

Servicios de salud: Los establecimientos de salud ofrecen sus servicios de salud a pacientes diabéticos con grandes limitaciones en recursos y medios clínicos para atender la enfermedad, lo que conduce irreversiblemente a amputaciones y discapacidad. Un medio relativo barato y de aplicación masiva como la termografía ayuda a enfrentarlo.

Altos costos: El tratamiento de enfermedades de difícil curación como el pie diabético requieren un continuo monitoreo médico y cuidados especiales en domicilio. Sea los servicios públicos o privados,

la demanda por atenciones de salud ha obligado a los países como el Perú a implementar programas específicos para diabetes y pie diabético, con registro de pacientes.   Siendo el pie diabético una patología multifactorial, el número de consultas por paciente es alto, los tratamientos disponibles tienen efectividad relativa, los fármacos suelen ser costosos y adicionalmente los pacientes tienen asociados otros síntomas que requieren ser atendidos y aliviados, sin que ello signifique la cura de la enfermedad. Todo este conjunto de factores hacen del pie diabético una enfermedad de alto costo para el paciente y el sistema de salud. La termografía ofrece una posibilidad de evitar llegar a este estado a un costo reducido.

Baja calidad de vida: El continuo monitoreo de temperatura del pie puede reducir la incidencia de condiciones indeseables tales como úlceras y amputaciones de miembros inferiores.   Estos transtornos limitan dramáticamente el desenvolvimiento de las personas en sus actividades diarias, haciéndose dependientes de personas de apoyo o asistentes que en muchos casos involucra a sus familiares. El monitoreo de temperatura puede hacerse mediante la termografía de forma no-invasiva y en un tiempo corto.

Efectividad clínica restringida: Para el diagnóstico y monitoreo no se han incorporado en el sistema de salud peruano el uso de medios cuantitativos no invasivos como la termografía, la cual permitiría rápidamente manejar indicadores cuantitativos para determinar el estado de gravedad del pie diabético.

c. Revisión de la Literatura:

El monitoreo de temperatura de la planta de pie es una indicación establecida por muchos autores [Roback,2010]   [Lavery, 2008] [Sun, 2006] [Armstrong, 2007] [Papanas, 2009] [Bahara, 2006] [Acharya, 2009] [Saxena, 2008] [Diakides, 2008]. La diferencia de temperatura en más de ±2.2°C es claramente una anormalidad a estudiar. Una diferencia menor a ±1.0°C entre ambos pies suele ser normal. La diferencia positiva esta relacionada a la inflamación e infección de los tejidos, sin embargo la diferencia negativa esta relacionada a deterioro arterial y neuropatias. Los medios para medición de temperatura pueden ser puntuales con termómetro en áreas de riesgo en la planta del pie, o mediante cristal líquido o por medio de imágenes termográficas basadas en infrarrojos. ¿Cuál es la mejor forma de medir la temperatura en la planta del pie? ¿Cuál es la temperatura base? ¿Existen zonas de mayor riesgo en la planta del pie? ¿Cuan efectivo es monitorear la temperatura del pie en relación al inicio de pie diabético?

d. Marco teórico:

Clínicamente la valoración del riesgo de pie diabético se reconoce como una medida efectiva de prevención. Muchos estudios muestran que la temperatura es un importante parámetro en la evaluación preventiva de pie diabético, pero pocos han estudiado qué se podría ganar en la reducción de las complicaciones y mejora de la salud. Las imágenes termográficas obtenidas con cámara infrarroja representan un mapeo de temperatura en toda la extensión de la planta del pie. La imagen es procesada en computadora para determinar los puntos de mayor o menor temperatura para su análisis respecto al deterioro de los tejidos. El uso de esta herramienta aunado a la valoración del riesgo de pie diabético mejoraría la capacidad de predicción de aparición de lesiones severas (Úlceras o gangrena seca)

e. Objetivo General:

El objetivo principal de esta investigación es establecer la correlación entre las diferencias de temperatura (patrones o zonas de calor) en el pie obtenidas por termografía y el deterioro estructural de los tejidos blandos, a fin de ser un parámetro cuantitativo en el diagnóstico preventivo del pie diabético.

Objetivos Específicos:
a. Validar el protocolo de reclutamiento de pacientes.
b. Validar el protocolo de adquisición de imágenes termográficas
c. Verificar los patrones de temperatura en las zonas de calor relacionados al deterioro estructural del tejido blando y los patrones morfológicos patológicos a nivel histológico que anteceden a la ulceración de una herida.
d. Validar el algoritmo de comparación y cálculo de la termografía infrarroja como método cuantitativo.
e. Evaluar la efectividad clínica de aplicación de termografía en la determinación de riesgo de pie diabético.

4. Hipótesis del Proyecto:

Las diferencias de temperatura y su variación en el tiempo pueden ser indicadores válidos para determinar de forma preventiva el riesgo de ulceración en pie diabético. Para la discriminación estadística, se calculará el tamaño de muestra apropiada de pacientes. De esta forma se podría establecer que el diagnóstico y monitoreo sistemático de complicaciones de pie diabético puede ser realizado utilizando termografía infrarroja con el objeto de detectar de manera precoz las áreas que están presentando deterioro estructural - biomecánico de los tejidos blandos.

5. Metodología

A. Tipo de estudio: Caso-control.
B. Área donde se realizará el estudio: Servicio de Endocrinología HNDM
C. Población y muestra: A determinar
D. Criterios de selección o reclutamiento:

Criterios de inclusión
a) Pacientes entre 30 y 75 años con diagnóstico de diabetes tipo 2 y de alto riesgo.
b) Pacientes de ambos sexos
c) Pacientes que otorguen su consentimiento por escrito para su inclusión en el estudio.
d) Pacientes que se encuentren en el nivel 0, según la escala de Wagner.

Criterios de exclusión
a) Pacientes con enfermedades neurodegenerativas.
b) Pacientes en edad pediátrica
c) Presencia actual de: pancreatitis aguda, colecistitis aguda, ictericia obstructiva o colangitis
d) Esferocitosis hereditaria
e) Mujeres embarazadas o lactantes
f) Pacientes con intención de donar sangre en el transcurso del estudio;
g) Imposibilidad de otorgar su consentimiento informado
h) Pacientes participantes en otros estudios de investigación.

i) Pacientes que se encuentren en los niveles 2 – 5, según la escala de Wagner.

j) Lesiones ulcerosas con área < 1 cm^2.

k) Presencia de procesos oncoproliferativos y/o enfermedades crónicas descompensadas: Cardiopatía isquémica, Diabetes mellitus (cetoacidosis y/o coma diabético), Insuficiencia renal (creatinina >200 mmol/L + oligoanuria).

l) Portadores de enfermedades psiquiátricas que le impedían dar su consentimiento informado.

Criterios de retirada

a) Los pacientes podrán ser retirados del estudio por alguna de las siguientes razones:

1.- El paciente decide no continuar en el estudio y/o con las visitas de seguimiento;

2.- El paciente no colabora o incumple los criterios de seguimiento.

b) Se retirarán del estudio a los pacientes con su HTA no controlada. El investigador modificará el tratamiento a su criterio.

E. Variables:

Se esperan variaciones de menos de 1° C, siendo que las variaciones superiores a 2.2° C se consideran claramente anormales. El mapeo de Temperatura con imágenes termográficas permitirá finalmente establecer patrones de zonas de calor; las mismas que deberán correlacionarse positivamente con daños estructurales de los tejidos, daños que serán estimados con modelos biofísicos de transferencia de calor entre las diferentes transiciones de fase que caracterizan como biomaterial natural al tejido blando sano, degenerado y regenerado del pie diabético antes y durante la ulceración. Se analizará el perfil térmico, estimación de profundidades, cuantificación de áreas – distancias y el reconocimiento de características fisiopatológicas.

6. Referencias Bibliográficas:

1. **Amputación del miembro inferior por pie diabético en hospitales de la costa norte peruana 1990 - 2000: características clínico-epidemiológicas.** David Escalante Gutiérrez 1; Leonid Lecca García 2; Julio Gamarra Sánchez 1; Giannina Escalante Gutiérrez 1. Universidad Nacional de Trujillo. La Libertad, Perú. 2 Instituto Nacional de Salud. Lima, Perú.

2. **An overview of temperature monitoring devices for early detection of diabetic foot disorders.** Kerstin Roback, Center for Medical Technology Assessment (CMT), Department of Medical and Health Sciences, Linköping University, Sweden. Expert Rev. Med. Devices 7(5), 711–718 (2010).

3. **Resource utilisation and costs associated with the treatment of diabetic foot ulcers. Prospective data from the Eurodiale Study.** Prompers L, Huijberts M, Schaper N et al. Diabetologia 51(10), 1826–1834. (2008).

4. **Counting the costs of the diabetic foot.** Apelqvist J, Ragnarson Tennvall G. Diabetes Voice 50(Special Issue), 8–10. (2005).

5. **Preventing diabetic foot ulcer recurrence in high-risk patients: use of temperature monitoring as a selfassessment tool.** Lavery LA, Higgins KR, Lanctot DR et al. Diabetes Care 30(1), 14–20 (2007).

6. **New developments in diagnosing and treating diabetic foot infections.** Lipsky BA. Diabetes Metab. Res. Rev.24 (Suppl. 1), S66–S71 (2008).

7. **Delivery of care to diabetic patients with foot ulcers in daily practice: results of the Eurodiale Study, a prospective cohort study.** Prompers L, Huijberts M, Apelqvist J et al. Diabet. Med. 25, 700–707. (2008).

8. **Use of liquid crystal thermography in the evaluation of the diabetic foot.** Stess RM, Sisney PC, Moss KM et al. Diabetes Care 9(3), 267–272 (1986).

9. **A prospective study of risk factors for diabetic foot ulcer.** Boyko EJ, Ahroni JH, Stensel V, Forsberg RC, Davignon DR, Smith DG. The Seattle Diabetic Foot Study. Diabetes Care 22, 1036–1042. (1999).
10. **Relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet.** Sun PC, Lin HD, Jao SH, Ku YC, Chan RC, Cheng CK. Diabetes Res. Clin. Pract. 73(1), 41–46. (2006).
11. **Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients.** Armstrong DG, Holtz-Neiderer K, Wendel C, Mohler MJ, Kimbriel HR, Lavery LA. Am. J. Med. 120(12), 1042–1046 (2007).
12. **Monitoring neuropathic ulcer healing with infrared dermal thermometry.**Armstrong DG, Lavery LA. J. Foot Ankle Surg.
13. 35(4), 335–338 (1996).
14. **Skin temperatures as a one-time screening tool do not predict future diabetic foot complications.** Armstrong DG, Lavery LA, Wunderlich RP, Boulton AJ. J. Am. Podiatr. Med. Assoc. 93(6), 443–447 (2003).
15. **Does dermal thermometry predict clinical outcome in diabetic foot infection?** Armstrong DG, Lipsky BA, Polis AB, Abramson MA. Analysis of data from the SIDESTEP* trial. Int. Wound J. 3(4), 302–307 (2006).
16. **Foot temperature in Type 2 diabetic patients with or without peripheral neuropathy.** Papanas N, Papatheodorou K, Papazoglou D, Monastiriotis C, Maltezos E. Exp. Clin. Endocrinol. Diabetes 117(1), 44–47 (2009).
17. **How effective is manual palpation in detecting subtle temperature differences?** Murff RT, Armstrong DG, Lanctot D, Lavery LA, Athanasiou KA. Clin. Podiatr. Med. Surg. 15(1), 151–154. (1998).
18. **Clinical practice recommendations 2009.** American Diabetes Association. Diabetes Care 32, S1–S98 (2009).
19. **Thermography and thermometry in the assessment of diabetic neuropathic foot: a case for furthering the role of thermal techniques.** Bharara M, Cobb JE, Claremont DJ. Int. J. Low Extrem. Wounds 5(4), 250–260 (2006).
20. **Home monitoring of foot skin temperatures to prevent ulceration.** Lavery LA, Higgins KR, Lanctot DR et al. Diabetes Care 27(11), 2642–2647 (2004).
21. **Feasibility of a thermographic method for early detection of foot disorders in diabetes.** Roback K, Johansson M, Starkhammar A. Diabetes Technol. Ther. 11(10), 663–667. (2009).
22. **Diabetic foot self examination with the Tempstat™ as an integral component of a comprehensive prevention program.** Frykberg RG, Tallis A, Tierney E. J. Diabet. Foot Complications 1(1), 13–18. (2009).
23. **Application and value of liquid crystal thermography.** Dribbon B. J. Am. Podiatr. Assoc. 73, 400–404 (1983).
24. **Cold immersion recovery responses in the diabetic foot with neuropathy.** Bharara M, Viswanathan V, Cobb JE. Int. Wound J. 5(4), 562–569 (2008).
25. **Warm immersion recovery test in assessment of diabetic neuropathy – a proof of concept study.** Bharara M, Viswanathan V, Cobb JE. Int. Wound J. 5(4), 570–576 (2008).
26. **Temptouch®: infrared thermometer device for prevention of foot ulcers in people with diabetes.** Parrella A, Hiller J, Mundy L. Adelaide Health Technology Assessment. Horizon Scanning Prioritising Summary – Volume 10 (Brief record) (2005).
27. **Education, psychology and compliance.** Price PE. Diabetes Metab. Res. Rev. 24(Suppl. 1), S101–S105 (2008).
28. **Reducing the burden of chronic wounds: prevention and management of the diabetic foot in the context of clinical guidelines.** Searle A, Gale L, Campbell R et al. J. Health Serv. Res. Policy. 13(Suppl. 3), 82–91 (2008).
29. **Projecting the future diabetes population size and related costs for the U.S.** Huang ES, Basu A, O'Grady M, Capretta JC. Diabetes Care 32(12), 2225–2229. (2009).
30. **Plantar pressure assessment.** Orlin MN, McPoil TG. Phys. Ther. 80(4), 399–409. (2000).
31. **Remote-sensing infrared thermography.** Ng, E.; Acharya, R.; Engineering in Medicine and Biology Magazine, IEEE. Volume 28, Issue 1, January-February 2009 Page(s):76 – 83. Digital Object Identifier 10.1109/MEMB.2008.931018.
32. **Infrared thermography: Experience from a decade of pediatric imaging.** Author(s): Saxena, AK; Willital, GH. Source: EUROPEAN JOURNAL OF PEDIATRICS Volume: 167 Issue: 7 Pages: 757-764 Published: 2008.
33. **Medical Infrared Imaging.** Author(s): Nicholas A. Diakides; Joseph D. Bronzino. CRC Press – Taylor & Francis Group. 2008
34. **Infrared imaging technology and biological applications.** Author(s): Kastberger, G; Stachl, R. Conference Information: 4th International Conference of Methods Techniques in Behavioral Research, Date: AUG 27-30,

2002 VRIJE UNIV AMSTERDAM NETHERLANDS. Source: BEHAVIOR RESEARCH METHODS INSTRUMENTS & COMPUTERS   Volume: 35. Issue: 3   Pages: 429-439   Published: 2003.

35. **Infrared imaging: making progress in fulfilling its medical promise.** Head, J.F.; Elliott, R.L.; Engineering in Medicine and Biology Magazine, IEEE. Volume 21, Issue 6, Nov.-Dec. 2002 Page(s):80 – 85. Digital Object Identifier 10.1109/MEMB.2002.1175142.

36. **Infrared functional imaging applied to Raynaud's phenomenon.** Merla, A.; Di Donato, L.; Di Luzio, S.; Farina, G.; Pisarri, S.; Proietti, M.; Salsano, F.; Romani, G.L.; Engineering in Medicine and Biology Magazine, IEEE. Volume 21, Issue 6, Nov.-Dec. 2002 Page(s):73 – 79. Digital Object Identifier 10.1109/MEMB.2002.1175141.

37. **Imaging of skin thermal properties with estimation of ambient radiation temperature.** Otsuka, K.; Okada, S.; Hassan, M.; Togawa, T.; Engineering in Medicine and Biology Magazine, IEEE. Volume 21, Issue 6, Nov.-Dec. 2002 Page(s):49 – 55. Digital Object Identifier 10.1109/MEMB.2002.1175138.

38. **Advances in medical infrared imaging.** Diakides, N.A.; Engineering in Medicine and Biology Magazine, IEEE. Volume 21, Issue 6, Nov.-Dec. 2002 Page(s):32 – 33. Digital Object Identifier 10.1109/MEMB.2002.1175134.

39. **Cardiothermographic assessment of arterial and venous revascularization.** Szabo, T.; Fazekas, L.; Geller, L.; Horkay, F.; Merkely, B.; Gyongy, T.; Juhasz-Nagy, A.; Engineering in Medicine and Biology Magazine, IEEE. Volume 19, Issue 3, May-June 2000 Page(s):77 – 82. Digital Object Identifier 10.1109/51.844384.

40. **Investigating deep venous thrombosis with infrared imaging.** Harding, J.R.; Engineering in Medicine and Biology Magazine, IEEE. Volume 17, Issue 4, July-Aug. 1998 Page(s):43 – 46. Digital Object Identifier 10.1109/51.687962.

41. **Pathophysiological expression and analysis of far infrared thermal images.** Fujimas, I.; Engineering in Medicine and Biology Magazine, IEEE. Volume 17, Issue 4, July-Aug. 1998 Page(s):34 – 42. Digital Object Identifier 10.1109/51.687961

42. **Evaluating asymmetrical thermal distributions through image processing.** Mabuchi, K.; Chinzei, T.; Fujimasa, I.; Haeno, S.; Motomura, K.; Abe, Y.; Yonezama, T.; Engineering in Medicine and Biology Magazine, IEEE. Volume 17, Issue 2, March-April 1998 Page(s):47 – 55. Digital Object Identifier 10.1109/51.664030.

43. **Dynamical infrared thermography in humans.** Gulyaev, Yu.V.; Markov, A.G.; Koreneva, L.G.; Zakharov, P.V.; Engineering in Medicine and Biology Magazine, IEEE. Volume 14, Issue 6, Nov.-Dec. 1995 Page(s):766 – 771. Digital Object Identifier 10.1109/51.473272

Bibliografía:

44. **Medical Devices; Current Good Manufacturing Practice (CGMP) Final Rule; Quality System Regulation.** DEPARTMENT OF HEALTH AND HUMAN SERVICES. Food and Drug Administration. 21 CFR Parts 808, 812, and 820. [Docket No. 90N–0172]. RIN 0910–AA09. 1996.

45. **Environment, Safety, and Health Information Technology Systems Integration. Gregory W. Bayer, David A. Hendrickson.** Prepared by Sandia National Laboratories. Albuquerque, New Mexico 87185 and Livermore, California 94550. SAND2006-0782. Unlimited Release. Printed February 2006.

46. **Systematic Reviews in Health Care: Meta-Analysis in Context**. Matthias Egger, George Davey Smith, Douglas Altman. BMJ Publishing Group 2001.

47. **Medical Device Development: The Challenge for Ergonomics.** Jennifer L Martin[1], Beverley J Norris[2], Elizabeth Murphy[3], John A. Crowe[1]. 1 School of Electrical and Electronic Engineering, The University of Nottingham, University Park, Nottingham, NG7 2RD. UK. 2 National Patient Safety Agency, 4-8 Maple Street London, W1T 5HD. UK. 3 School of Sociology and Social Policy, The University of Nottingham, University Park, Nottingham, NG7 2RD. UK. 2005.

48. **Design by documentation: a method and case study**
Manwaring, M.L.; Malbasa, V.D.; Manwaring, K.H. Computer-Based Medical Systems, 1995., Proceedings of the Eighth IEEE Symposium on Volume , Issue , 9-10 Jun 1995 Page(s):272 – 277. Digital Object Identifier 10.1109/CBMS.1995.465416.

49. **MICROWAVE THERMOGRAPHY - PRINCIPLES, METHODS AND CLINICAL APPLICATIONS.** Author(s): MYERS, PC; SADOWSKY, NL; BARRETT, AH. Source: JOURNAL OF MICROWAVE POWER AND ELECTROMAGNETIC ENERGY   Volume: 14. Issue: 2   Pages: 105-115. Published: 1979.

50. **THERMOGRAPHY - CANADIAN INVENTION FINDING WIDER APPLICATIONS.** Author(s): OLIVER, C. Source: CANADIAN MEDICAL ASSOCIATION JOURNAL   Volume: 117   Issue: 6   Pages: 680-& Published: 1977.

51. **Energy-Based Diagnostic and Treatment Techniques.** Lisa Xu; Aili Zhang; Ping Liu; Chao Chen; Jianqi Sun; Sabados, D.; Engineering in Medicine and Biology Magazine, IEEE. Volume 27, Issue 5, September-October 2008 Page(s):72 – 77. Digital Object Identifier 10.1109/MEMB.2008.923960.
52. **Clinical thermal imaging today.** Anbar, M.; Engineering in Medicine and Biology Magazine, IEEE. Volume 17, Issue 4, July-Aug. 1998 Page(s):25 – 33. Digital Object Identifier 10.1109/51.687960.

ANEXOS

CONSENTIMIENTO INFORMADO DEL PACIENTE O COLABORADOR

Yo,……………………………………………………………………Nº……………

DNI…………………………………………………..

He leído la hoja informativa que me ha sido entregada 2

He tenido oportunidad de efectuar preguntas sobre el estudio.

He recibido respuestas satisfactorias.

He recibido suficiente información en relación con el estudio.

He hablado con el Dr./Investigador:

Entiendo que la participación es voluntaria.

Entiendo que puedo abandonar el estudio:

• Cuando lo desee.

• Sin que tenga que dar explicaciones.

• Sin que ello afecte a MIS cuidados médicos.

También he sido informado de forma clara, precisa y suficiente de los siguientes extremos que afectan a los datos personales que se contienen en este consentimiento y en la ficha o expediente que se abra para la investigación:

•Estos datos serán tratados y custodiados con respeto a mi intimidad y a la vigente normativa de protección de datos.

 •Sobre estos datos me asisten los derechos de acceso, rectificación, cancelación y oposición que podré ejercitar mediante solicitud ante el investigador responsable en la dirección de contacto que figura en este documento.

•Estos datos no podrán ser cedidos sin mi consentimiento expreso y no lo otorgo en este acto.

Doy mi consentimiento sólo para la extracción necesaria en la investigación de la que se me ha informado y para que sean utilizadas las muestras (fluidos, tejidos, etc...) exclusivamente en ella, sin posibilidad de compartir o ceder éstas, en todo o en parte, a ningún otro investigador, grupo o centro distinto del responsable de esta investigación o para cualquier otro fin.

Declaro que he leído y conozco el contenido del presente documento, comprendo los compromisos que asumo y los acepto expresamente. Y, por ello, firmo este consentimiento informado de forma voluntaria para MANIFESTAR MI DESEO DE PARTICIPAR EN ESTE ESTUDIO DE INVESTIGACIÓN SOBRE Determinación de la capacidad de predicción diagnóstica de lesiones finales en Pie Diabético a partir de exámenes periódicos de

termografía, hasta que decida lo contrario. Al firmar este consentimiento no renuncio a ninguno de mis derechos. Recibiré una copia de este consentimiento para guardarlo y poder consultarlo en el futuro.

Nombre del paciente o sujeto colaborador:
DNI:

Firma:

Fecha:

Nombre del investigador:
DNI:
Firma:

Identificación del Grupo responsable de la investigación: Lic. María Teresa Arista Rivera HNDM, MSc. Ing. Luis Alberto Vilcahuamán Cajacuri PUCP, Dr. Hugo Cesar Arbañil Huamán HNDM, MSc. Ing. José Ferrer PUCP

Fecha:
Dirección de contacto del Investigador y/o del Grupo de responsables de la investigación y del tratamiento de los datos: Programa de Diabetes HNDM / Servicio de Rehabilitación HNDM

NOTAS
1 Indicar el nombre completo
2 Incorporar de forma inseparable o al dorso de éste documento.

PROTOCOLO DE APLICACIÓN DE PRUEBAS TERMOGRAFICAS

El presente protocolo está orientado a mostrar la adecuada aplicación de la termografía como herramienta en el diagnóstico del pie diabético, asimismo nos brinda un alcance de las principales de señales de alerta que no pueden ser percibidas por el paciente.

REQUERIMIENTOS
- ✓ 1 camilla
- ✓ 1 atril para cámara
- ✓ 1 termógrafo
- ✓ 1 base de espuma de poliuretano
- ✓ 1 laptop

✓ 1 caja de guantes quirúrgicos

CONSIDERACIONES

La toma de las muestras requiere tener en cuenta:

Paciente debe reposar en la camilla con los pies descalzos por un periodo de 15 minutos para permitir la adecuada estabilización térmica de sus pies y no tener falsos positivos o falsos negativos.

La distancia entre la cámara y los pies no debe ser menor a 1.10cm.

Se realizaran entre 3 a 5 tomas a las plantas de los pies, tomando en consideración la actitud postural de los pies.

PRECAUCIONES

El presente estudio no representa ningún cambio a nivel fisiológico para el paciente, ni para el investigador.
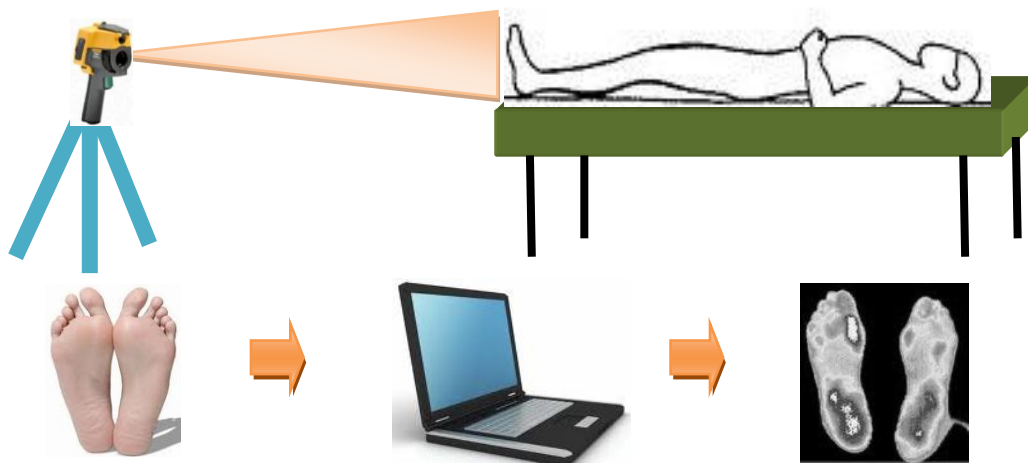
Appendix C: The 85 images of the medical study
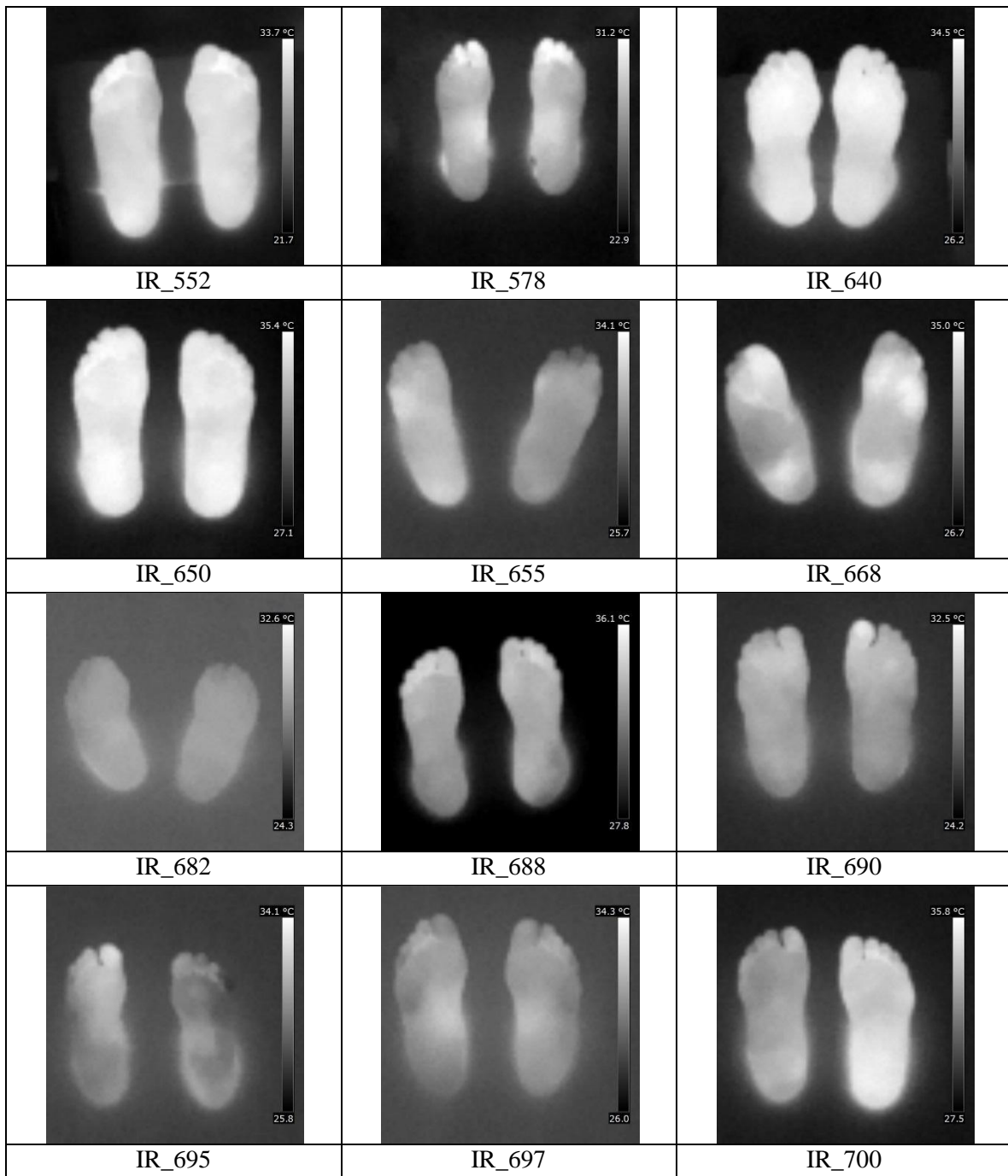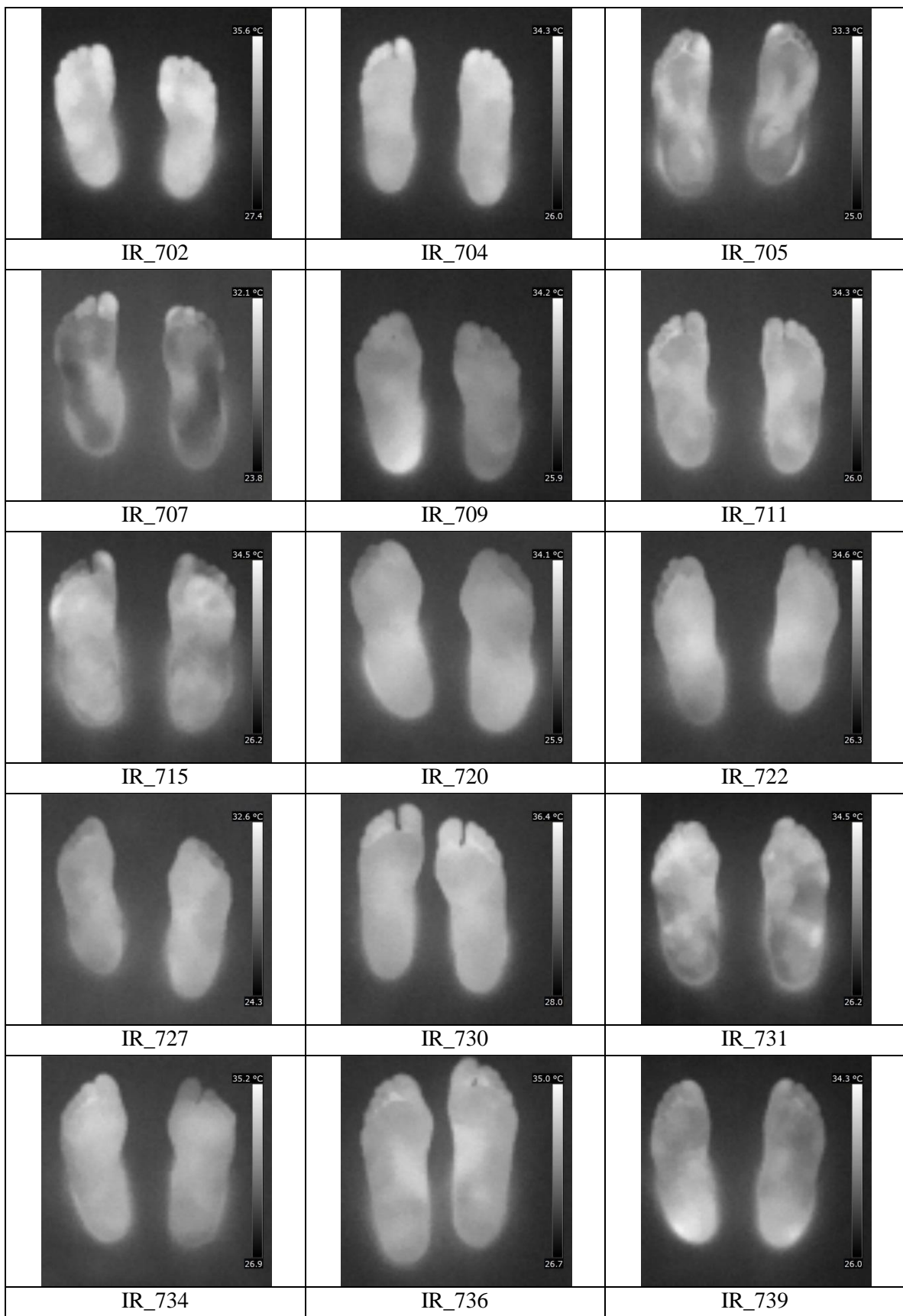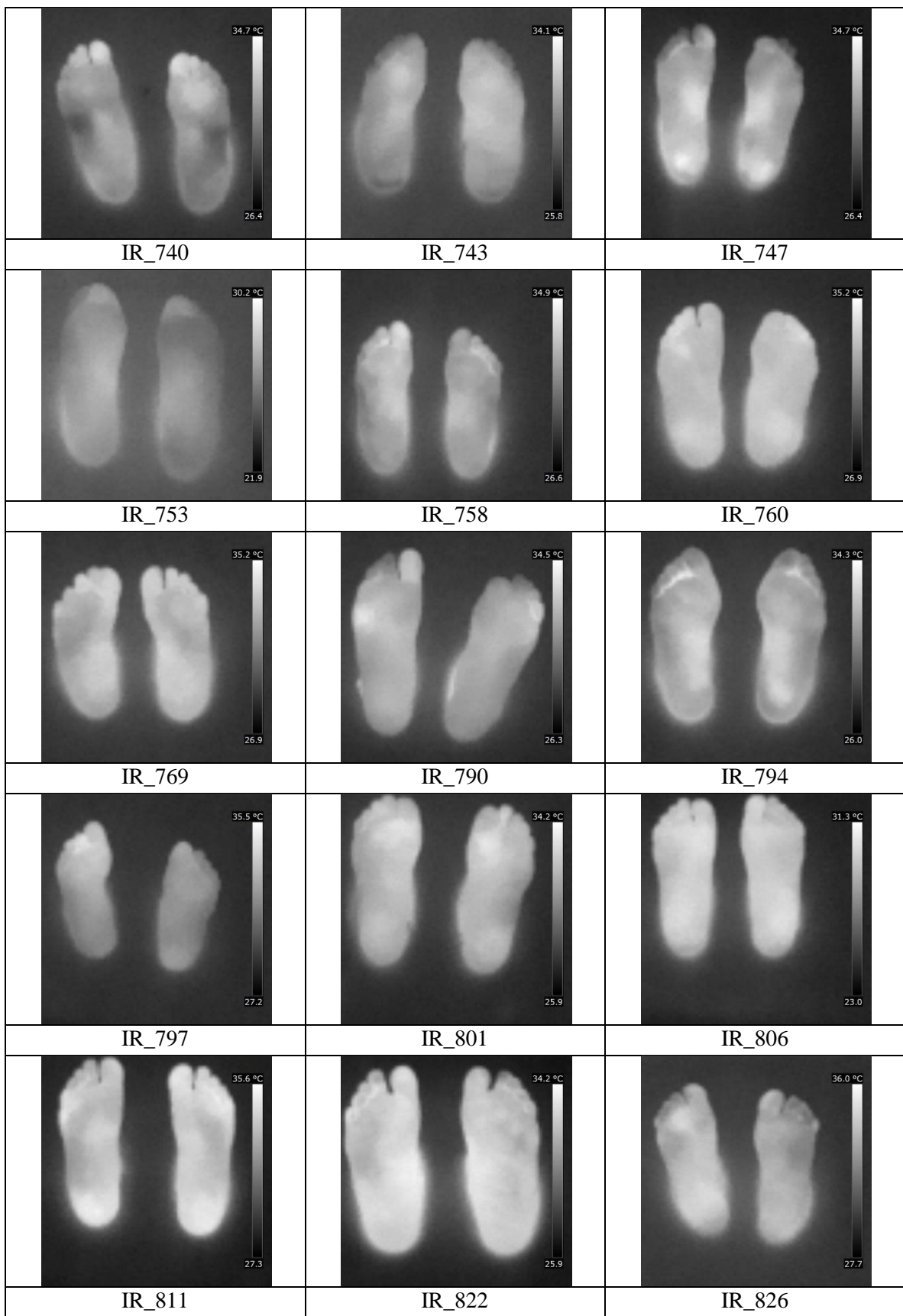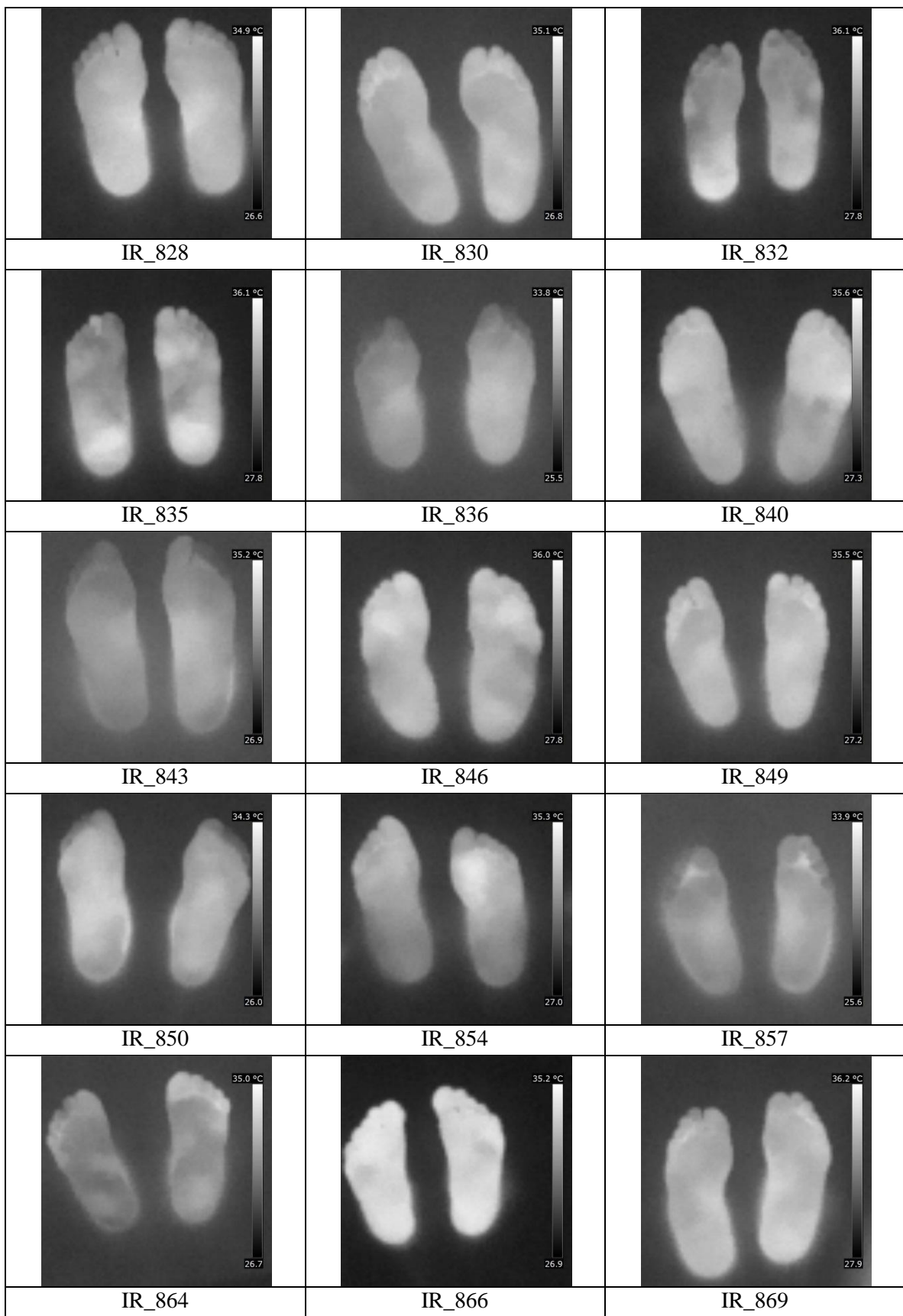
IR_552	IR_578	IR_640
IR_650	IR_655	IR_668
IR_682	IR_688	IR_690
IR_695	IR_697	IR_700

IR_702	IR_704	IR_705
IR_707	IR_709	IR_711
IR_715	IR_720	IR_722
IR_727	IR_730	IR_731
IR_734	IR_736	IR_739

IR_740	IR_743	IR_747
IR_753	IR_758	IR_760
IR_769	IR_790	IR_794
IR_797	IR_801	IR_806
IR_811	IR_822	IR_826

IR_828	IR_830	IR_832
IR_835	IR_836	IR_840
IR_843	IR_846	IR_849
IR_850	IR_854	IR_857
IR_864	IR_866	IR_869

IR_872	IR_875	IR_880
IR_881	IR_884	IR_888
IR_891	IR_895	IR_896
IR_900	IR_901	IR_903
IR_921	IR_951	IR_954

IR_956	IR_960	IR_966

IR_967	IR_972	IR_977
IR_978	IR_981	IR_983
IR_989	IR_992	IR_993
	IR_996	

Appendix D: Parameters of the 85 images of the medical study:

- |ΔT°| value (mean absolute value of the point to point difference between left and right feet),
- % (percentage of points such that |ΔT°| is greater than 2.2°C),
- ML: mean left temperature,
- MR: mean right temperature,
- SL: standard deviation of left foot,
- SR: standard deviation of right foot.

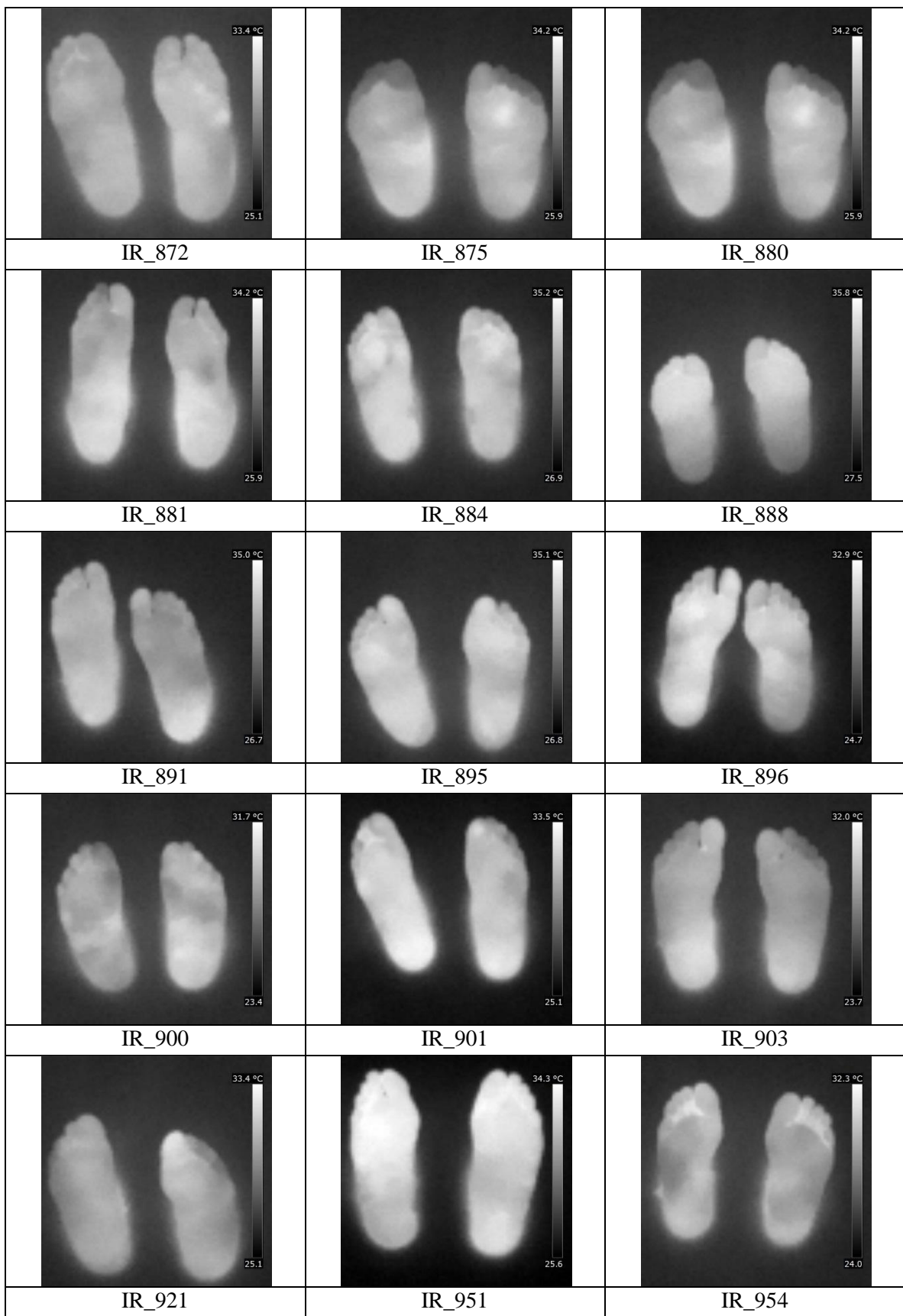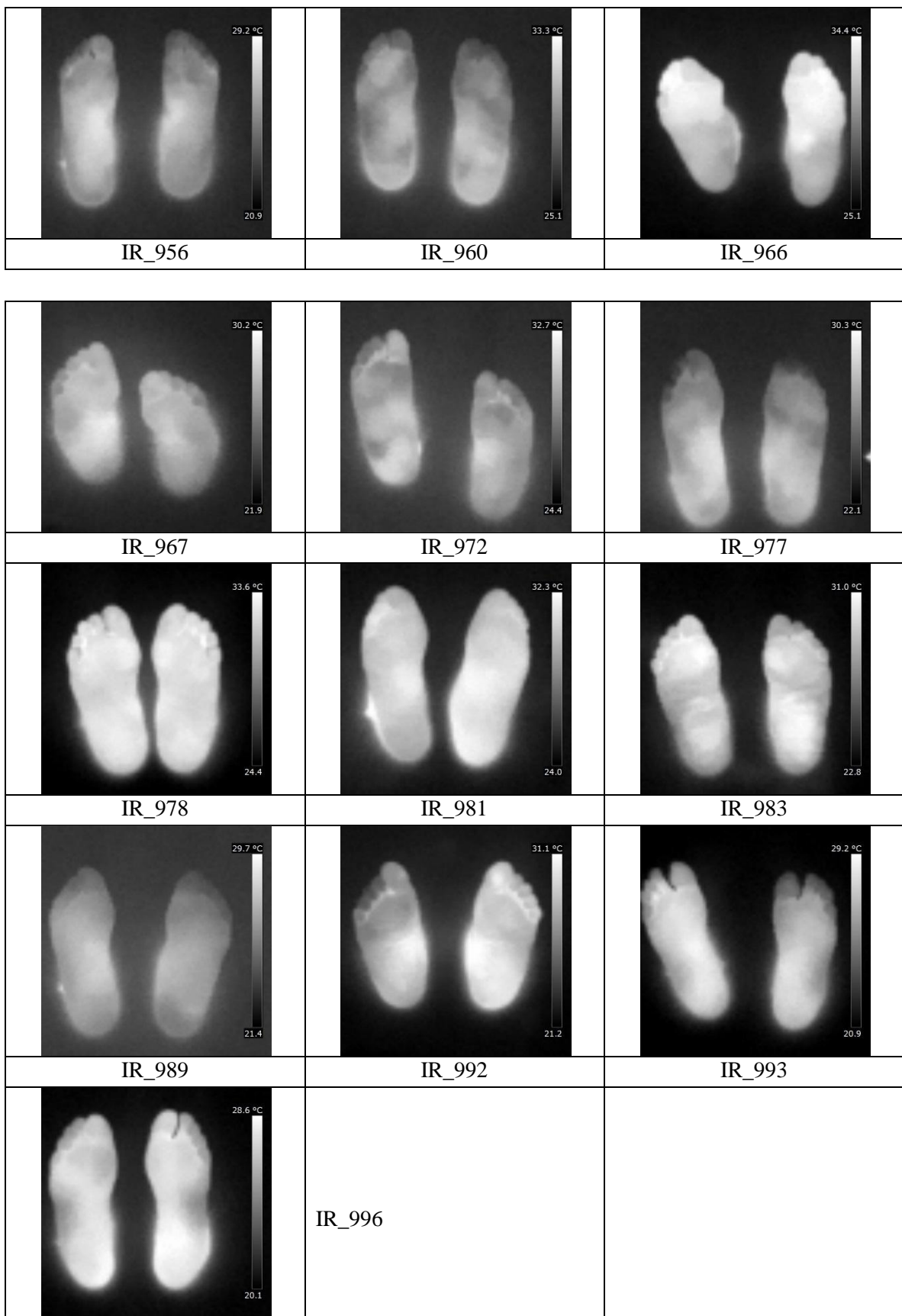| Image number	Risk	Disease	$|\Delta T°|$	%	ML	MR	SL	SR
578	High	Neuropathy	0,3025	0	28,8557	28,9541	0,8888	0,9257
640	High	Neuropathy	0,2263	0	33,5163	33,4010	0,6254	0,5524
650	High	Neuropathy	0,2264	0	34,7057	34,5314	0,4453	0,4536
688	High	Neuropathy	0,3760	0,0262	32,9493	33,1895	0,7680	0,6873
704	High	Neuropathy	0,3244	0,1486	31,9948	32,1291	0,5029	0,5883
711	High	Neuropathy	0,2887	0	31,5645	31,6642	0,4246	0,5069
790	High	Neuropathy	0,5803	0,4138	31,9059	31,5405	0,5342	0,5413
836	High	Neuropathy	0,7886	0	30,2574	31,046	0,4854	0,4888
846	High	Neuropathy	0,2985	0	33,7446	33,5126	0,5423	0,506
854	High	Neuropathy	0,5661	0	31,9491	32,3289	0,726	0,9978
866	High	Neuropathy	0,2929	0	33,8416	33,7523	0,4698	0,3961
869	High	Neuropathy	0,3665	0	33,6515	34,0005	0,4075	0,4463
888	High	Neuropathy	0,293	0	33,6307	33,3497	0,9261	0,9375
895	High	Neuropathy	0,4069	0,0221	33,2408	33,0725	0,4619	0,5768
951	High	Neuropathy	0,7286	0,0518	32,8839	32,8019	0,9893	0,6597
954	High	Neuropathy	0,4421	0,0212	29,5858	29,3939	0,7037	0,5023
966	High	Neuropathy	0,5549	0,6747	32,5617	32,8213	1,0744	1,1156
981	High	Neuropathy	0,727	3,8454	30,5451	31,0724	0,6752	0,6492
552	High	Neuropathy + Ischemia	0,4797	0,2216	31,7502	31,8114	0,7930	0,8025
655	High	Neuropathy + Ischemia	1,1553	0,0525	31,7719	30,6396	0,4838	0,3972
668	High	Neuropathy + Ischemia	0,7365	0,3889	32,5386	33,0764	0,9750	0,7016
682	High	Neuropathy + Ischemia	0,2622	0	29,4556	29,2749	0,3264	0,2663
707	High	Neuropathy + Ischemia	0,6895	0,1689	28,1603	27,5513	0,7650	0,6967
709	High	Neuropathy + Ischemia	1,0810	15,0967	31,0714	30,0184	0,8985	0,3606
720	High	Neuropathy + Ischemia	0,4278	0	31,4925	31,1310	0,5293	0,5461
734	High	Neuropathy + Ischemia	0,6732	1,3869	32,6486	31,9952	0,5178	0,5867
740	High	Neuropathy + Ischemia	0,6939	0,0825	31,2881	31,0985	0,7260	0,9444

760	High	Neuropathy + Ischemia	0,3032	0,0199	33,0616	33,1377	0,412	0,4266
828	High	Neuropathy + Ischemia	0,2916	0	32,4805	32,3224	0,6537	0,5193
850	High	Neuropathy + Ischemia	0,5738	0,1007	31,9445	31,4165	0,5851	0,4869
864	High	Neuropathy + Ischemia	0,797	0,1802	30,8969	31,6873	0,4539	0,555
891	High	Neuropathy + Ischemia	0,6948	0	32,5146	32,0223	0,4724	0,8104
967	High	Neuropathy + Ischemia	0,7728	0,1185	28,0094	27,2695	0,7117	0,7239
736	Low	Healthy	0,2723	0	32,1179	32,1966	0,5761	0,6211
747	Low	Healthy	0,4217	0	32,3476	31,9741	0,7394	0,7693
715	Low	Neuropathy	0,6242	0,1633	31,7846	31,3023	0,6115	0,6708
753	Medium	Healthy	0,7441	0	26,9934	26,2497	0,4277	0,5119
900	Medium	Healthy	0,6444	0	28,7013	29,2755	0,55	0,7086
977	Medium	Healthy	0,4991	0,0217	27,6362	27,2749	0,9213	0,8623
690	Medium	Neuropathy	0,3641	0	29,6295	29,4500	0,5354	0,7307
695	Medium	Neuropathy	0,8900	4,4082	30,8053	30,1110	0,8408	0,4572
697	Medium	Neuropathy	0,2545	0	31,0127	30,9474	0,6326	0,4635
700	Medium	Neuropathy	1,5761	4,7244	32,6948	34,2709	0,5431	0,6336
702	Medium	Neuropathy	0,3034	0,0253	33,7935	33,7603	0,5568	0,6068
705	Medium	Neuropathy	0,6947	0,1016	30,3843	29,7506	0,7014	0,7000
722	Medium	Neuropathy	0,3413	0	31,8619	31,8712	0,7446	0,5519
727	Medium	Neuropathy	0,5801	0	29,3438	29,9229	0,4642	0,4539
730	Medium	Neuropathy	0,3583	0	33,6784	33,9904	0,4453	0,4930
731	Medium	Neuropathy	0,6735	0	31,5701	31,2023	0,9381	0,6852
739	Medium	Neuropathy	0,6306	0	31,2014	30,6504	0,9441	0,7857
743	Medium	Neuropathy	0,5956	0	30,8648	31,4540	0,6348	0,5703
758	Medium	Neuropathy	0,4878	0,099	32,1717	31,8732	0,7561	0,4678
769	Medium	Neuropathy	0,374	0	32,7473	32,9604	0,6002	0,4766
794	Medium	Neuropathy	0,3237	0	31,702	31,5257	0,6718	0,6799
797	Medium	Neuropathy	0,8318	1,7444	32,486	31,778	0,888	0,4082
801	Medium	Neuropathy	0,2727	0	31,8755	31,7678	0,6007	0,6207
806	Medium	Neuropathy	0,2719	0	29,507	29,4139	0,5153	0,4815
811	Medium	Neuropathy	0,4285	0	33,5761	33,9282	0,6391	0,5527
822	Medium	Neuropathy	0,3716	0	32,6057	32,3498	0,5543	0,5268
826	Medium	Neuropathy	0,7843	0	33,7033	32,993	0,6545	0,605
830	Medium	Neuropathy	0,4022	0	32,4671	32,7028	0,3996	0,3881
832	Medium	Neuropathy	0,4169	0	32,9873	32,8658	0,9544	0,6867
835	Medium	Neuropathy	0,5161	0,5621	33,0327	33,3854	0,934	0,7759
840	Medium	Neuropathy	0,3549	0	33,0653	33,055	0,4666	0,6901
843	Medium	Neuropathy	0,5689	0	31,5103	32,0057	0,4572	0,5776
849	Medium	Neuropathy	0,4085	0	33,0278	33,4057	0,4029	0,3477
857	Medium	Neuropathy	0,4332	0	30,4187	30,8227	0,4436	0,4592

875	Medium	Neuropathy	0,626	0,0216	32,5804	32,0404	0,7267	0,6628
881	Medium	Neuropathy	0,3527	0,0382	32,0121	31,9923	0,7825	0,7191
884	Medium	Neuropathy	0,4277	0	33,4336	33,0678	0,5532	0,5674
896	Medium	Neuropathy	0,9358	6,6697	31,3641	30,4614	0,6575	0,7873
901	Medium	Neuropathy	0,656	0,0213	31,9614	31,3666	0,7085	0,6934
903	Medium	Neuropathy	0,618	0	29,4931	28,8888	0,733	0,6548
921	Medium	Neuropathy	0,4272	0	30,3031	30,4636	0,4637	0,733
956	Medium	Neuropathy	0,6877	0	26,5157	25,8859	0,8879	0,8009
960	Medium	Neuropathy	0,4951	0	30,1124	30,1613	0,667	0,8676
972	Medium	Neuropathy	0,6182	3,6549	29,9763	29,6229	0,7769	0,6916
978	Medium	Neuropathy	0,3016	0,1786	32,3054	32,1969	0,6305	0,6945
983	Medium	Neuropathy	0,668	0,1464	29,2611	29,3289	0,906	0,9019
989	Medium	Neuropathy	0,6331	0	26,8391	26,2477	0,6858	0,6631
992	Medium	Neuropathy	1,5304	18,1671	27,9369	29,4606	1,3	0,8474
993	Medium	Neuropathy	0,8315	0,0226	27,4429	26,6215	0,8841	1,0295
996	Medium	Neuropathy	0,555	0,3265	26,9709	27,1555	0,8117	0,9236
872	Medium	Neuropathy + Ischemia	0,473	0	30,6529	30,9639	0,3778	0,5157
880	Medium	Neuropathy + Ischemia	0,5811	0,3743	31,7513	31,7218	0,6867	0,6193

Bibliography

- ADA American Diabetes Association. Clinical practice recommendations 2009. Diabetes Care 32, S1–S98 (2009).

- ADA American Diabetes Association. Diagnosis and Classification of Diabetes Mellitus. Diabetes Care, Volume 35, Supplement 1, January 2012: S64 – S71.

- ADA American Diabetes Association. Peripheral arterial disease in people with diabetes. Diabetes Care 2003; 26:3333–3341.

- ADA American Diabetes Association. Standards of Medical Care in Diabetes - 2013. Diabetes Care, Volume 36, Supplement 1, January 2013: S11 – S66.

- Agardh E, Tababat-Khani P. Adopting 3-year screening intervals for sight-threatening retinal vascular lesions in type 2 diabetic subjects without retinopathy. Diabetes Care 2011;34:1318–1319.

- Ahmed J, Ward TP, Bursell SE, Aiello LM, Cavallerano JD, Vigersky RA. The sensitivity and specificity of nonmydriatic digital stereoscopic retinal imaging in detecting diabetic retinopathy. Diabetes Care 2006; 29:2205–2209.

- Alcantara W, Flores R, Garmendia F. Prevalencia y Riesgo de Amputación en Pacientes con Pie Diabético. Anales Fac Medicina. 1999; 60(3):159.

- Ammer K. 2008. The Glamorgan Protocol for recording and evaluation of thermal images of the human body. Thermol Int 18: 125–129

- Ammer, K. Ring, E.F.J. Standard procedures for infrared imaging in medicine, in: Biomedical Engineering Handbook, CRC Press, 2006. (Chapters 36-1 to 36-14).

- Anbar M, Milescu L. Prerequisites of dynamic area telethermometry (DAT). Proceedings of the 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 1998 29 Oct–Nov 1; Hong Kong.

- Andersen CA, Roukis TS. The Diabetic Foot. Surg Clin North Am. 2007 Oct;87(5):1149-77.

- Anderson M.E., Moore T.L., Lunt M, Herrick A.L. 2007. The 'distal–dorsal difference': a thermographic parameter by which to differentiate between primary and secondary Raynaud's phenomenon. Rheumatology 46: 533–538.

- Apelqvist, J.; Bakker, K.; van Houtum ,W. H.; Schaper, N. C. Practical guidelines on the management and prevention of the diabetic foot. Diabetes/metabolism research and reviews. Diabetes Metab Res Rev 2008; 24 (Suppl 1): S181–S187.

- Armstrong DG, Holtz-Neiderer K, Wendel C, Mohler MJ, Kimbriel HR, Lavery LA. Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients. Am. J. Med. 120(12), 1042–1046 (2007).

- Armstrong DG, Lavery LA, Wunderlich RP, Boulton AJ. Skin temperatures as a one-time screening tool do not predict future diabetic foot complications. J. Am. Podiatr. Med. Assoc.93(6), 443–447 (2003).

- Armstrong DG, Lavery LA. Monitoring neuropathic ulcer healing with infrared dermal thermometry. J. Foot Ankle Surg. 35(4), 335–338 (1996).

- Armstrong DG, Lipsky BA, Polis AB, Abramson MA. Does dermal thermometry predict clinical outcome in diabetic foot infection? Analysis of data from the SIDESTEP* trial. Int. Wound J. 3(4), 302–307 (2006).

- Attinger CE, Evans KK, Bulan E, et al. Angiosomes of the foot and ankle and clinical implications for limb salvage: Reconstruction, incisions, and revascularization. Plast Reconstr Surg 2006; 117:261S-93S.

- Baigent C, Blackwell L, Collins R, et al.; Antithrombotic Trialists' (ATT) Collaboration. Aspirin in the primary and secondary prevention of vascular disease: collaborative meta-analysis of individual participant data from randomised trials. Lancet 2009;373:1849–1860.

- Bakker, K.; Apelqvist, J.; Schaper, N.C. Practical guidelines on the management and prevention of the diabetic foot 2011. International Working Group on the Diabetic Foot Editorial Board IWGDF and Diabetes Metab Res Rev 2012; 28 (Suppl 1): 225–231.

- Bax JJ, Young LH, Frye RL, Bonow RO, Steinberg HO, Barrett EJ; ADA. Screening for coronary artery disease in patients with diabetes. Diabetes Care 2007;30: 2729–2736.

- Belch J, MacCuish A, Campbell I, Cobbe S, Taylor R, Prescott R, Lee R, Bancroft J, MacEwan S, Shepherd J, Macfarlane P, Morris A, Jung R, Kelly C, Connacher A, Peden N, Jamieson A,Matthews D, Leese G, McKnight J, O'Brien I, Semple C, Petrie J, Gordon D, Pringle S, MacWalter R: The prevention of progression of arterial disease and diabetes (POPADAD) trial: factorial randomised placebo controlled trial

of aspirin and antioxidants in patients with diabetes and asymptomatic peripheral arterial disease. BMJ 2008; 337:a1840.

- Berl T, Hunsicker LG, Lewis JB, et al.; Irbesartan Diabetic Nephropathy Trial. Collaborative Study Group. Cardiovascular outcomes in the Irbesartan Diabetic Nephropathy Trial of patients with type 2 diabetes and overt nephropathy. Ann Intern Med 2003;138: 542–549.

- Besl, P., McKay, N. A method for registration of 3-D shapes. IEEE Transaction on pattern analysis and machine intelligence, Vol. 14, No.2, February 1992. 239-256.

- Bezdek, J., Ehrlich, R., Full, W. FCM: The fuzzy c-means clustering algorithm. Computers & Geosciences Vol. 10, No. 2-3, pp. 191-203, 1984.

- Bezdek, J.C., Hall, L.O., Clarke, L.P.: Review of MR Image Segmentation Techniques Using Pattern Recognition. Med. Phys., Vol. 20, 1993, pp. 1033–1048.

- Bhan, R.K.; Saxena, R.S.; Jalwania, C.R. and Lomash S.K. Uncooled Infrared Microbolometer Arrays and their Characterization Techniques - REVIEW PAPER. Solid State Physics Laboratory, Delhi-110 054. Defence Science Journal, Vol. 59, No. 6, November 2009, pp. 580-589. 2009.

- Bharara M, Cobb JE, Claremont DJ. Thermography and thermometry in the assessment of diabetic neuropathic foot: a case for furthering the role of thermal techniques. Int. J. Low Extrem. Wounds 5(4), 250–260 (2006).

- Boulton AJ, Armstrong DG, Albert SF, et al.; American Diabetes Association; American Association of Clinical Endocrinologists. Comprehensive foot examination and risk assessment: a report of the task force of the foot care interest group of the American Diabetes Association, with endorsement by the American Association of Clinical Endocrinologists. Diabetes Care 2008; 31:1679–1685.

- Boulton AJ, Vinik AI, Arezzo JC, Bril V, Feldman EL, Freeman R, Malik RA, Maser RE, Sosenko JM, Ziegler D. Diabetic neuropathies: a statement by the American Diabetes Association. Diabetes Care. 2005 Apr;28(4):956-62.

- Boyer DS. Ranibizumab (anti-VEGF) for vision loss due to diabetic macular edema: reslts of two phase III randomized trials. 2011.

- Boyko, E.J.; Ahroni, J.H.; Stensel, V.L. Skin temperature in the neuropathic diabetic foot, J. Diabetes Complications 15 (2001). 260–264.

- Bril V, England J, Franklin GM, et al.; American Academy of Neurology; American Association of Neuromuscular and Electrodiagnostic Medicine; American Academy of Physical Medicine and Rehabilitation. Evidence-based guideline: Treatment of painful diabetic neuropathy: report of the American Academy of Neurology, the American Association of Neuromuscular and Electrodiagnostic Medicine, and the

American Academy of Physical Medicine and Rehabilitation. Neurology 2011;76:1758–1765.

- Buse JB, Ginsberg HN, Bakris GL, et al.; American Heart Association; American Diabetes Association. Primary prevention of cardiovascular diseases in people with diabetes mellitus: a scientific statement from the American Heart Association and the American Diabetes Association. Diabetes Care 2007;30:162–172.

- Chew EY, Ambrosius WT, Davis MD, et al.; ACCORD Study Group; ACCORD Eye Study Group. Effects of medical therapies on retinopathy progression in type 2 diabetes. NEngl J Med 2010; 363:233–244.

- Chambers, R., Elftman, N., Bowker, J. Orthotic management of the neuropathic and/or dysvascular patient. AAOS atlas of orthoses and assistive devices. Edited by John D. Hsu, John W. Michael, John R. Fisk.—4th ed; 2008: 391-409.

- Chan AW, MacFarlane IA, Bowsher DR. Contact thermography of painful diabetic neuropathic foot. Diabetes Care 1991;14:918e22.

- Chan, T. & Vese, L. Active contours without edges. IEEE Transactions on image processing, vol. 10, No. 2, February 2001.

- Chen, H.S. Hwu, C.M. Kuo, B.I. Abnormal cardiovascular reflex tests are predictors of mortality in type 2 diabetes mellitus, Diabet. Med. 18 (2001) 268–273.

- Collins R, Armitage J, Parish S, Sleigh P, Peto R; Heart Protection Study Collaborative Group. MRC/BHF Heart Protection Study of cholesterol-lowering with simvastatin in 5963 people with diabetes: a randomised placebo-controlled trial. Lancet 2003;361:2005–2016

- Constantinides GP. Thermometric apparatus and method. US6090050 (2000).

- De Weerd L., Mercer J.B., Setsa L.B. 2006. Intraoperative dynamic infrared thermography and free flap surgery; Ann Plast Surg 57: 279–284

- Denoble A.E., Hall N., Pieper C.F., Kraus V.B. 2010. Patellar skin surface temperature by thermography reflects knee osteoarthritis severity. Clini Med Insights: Arthritis Musculoskel Disorders 3: 69–75.

- Diakides I, Nicholas A, Bronzino J. Medical Infrared Imaging. CRC Press. Cap. 1. I12-I13. 2007.

- Dungan KM, Braithwaite SS, Preiser JC 2009 Stress hyperglycaemia. Lancet 373:1798–1807.

- Feldman, E.L.; Stevens, M.J.; Thomas, P.K.; Brown, M.B.; Canal, N.; Greene, D.A. A practical two steps quantitative clinical electrophysiological assessment for the diagnosis and staging diabetic neuropathy, Diabetes Care 11 (1994) 1281–1289.

- FLIR Systems AB. Thermal imaging guidebook for industrial applications. 2011.

- FLIR. Uncooled detectors for thermal imaging cameras. Technical note. FLIR Commercial Vision Systems B.V. www.flir.com (accessed January 2013).

- FLIR Systems, User manual i5. Publication T559018 Rev a298 – English, July 29, 2008.

- Fong DS, Aiello LP, Ferris FL 3rd, Klein R. Diabetic retinopathy. Diabetes Care 2004;27:2540–2553.

- FLUKE, Industrial/Commercial thermal imagers models: Ti25, Ti10 and Ti9 – Technical Data. 2010.

- Fonseca C, Abraham D, Ponticos M. 2009. Neuronal regulators and vascular dysfunction in Raynaud's phenomenon and systemic sclerosis; Curr Vasc Pharmacol 7: 34–3

- Ford ES. Trends in the risk for coronary heart disease among adults with diagnosed diabetes in the U.S.: findings from the National Health and Nutrition Examination Survey, 1999-2008. Diabetes Care 2011;34:1337–1343.

- Fosse S, Hartemann-Heurtier A, Jacqueminet S, Ha Van G, Grimaldi A, Fagot-Campagna A. Incidence and Characteristics of Lower Limb Amputations in People with Diabetes. Diabet Med. 2009; 26(4):391-6.

- Frize M, Adea C., Payeur P. et al. 2011 Detection of rheumatoid arthritis using infrared imaging; Proc. SPIE 7962, 79620M; Medical imaging 2011: Image processing, 14 February 2011. Lake Buena Vista, USA

- Frye RL, August P, Brooks MM, et al.; BARI 2D Study Group. A randomized trial of therapies for type 2 diabetes and coronary artery disease. N Engl J Med 2009; 360:2503–2515.

- Frykberg RG, Tallis A, Tierney E. Diabetic foot self-examination with the Tempstat™ as an integral component of a comprehensive prevention program. J. Diabet. Foot Complications 1(1), 13–18 (2009).

- Gaede P, Lund-Andersen H, Parving HH, Pedersen O. Effect of a multifactorial intervention on mortality in type 2 diabetes. N Engl J Med 2008;358:580–591.

- Gautherie M., Thermobiological assessment of benign and malignant breast diseases, Am. J. Obstet Gynecol. (8) 147 (1983) 861–869.

- Goldberg RB,Mellies MJ, Sacks FM, et al.; The Care Investigators. Cardiovascular events and their reduction with pravastatin in diabetic and glucose-intolerant myocardial infarction survivors with average cholesterol levels: subgroup analyses in the cholesterol and recurrent events (CARE) trial. Circulation 1998;98:2513–2519.

- Gorbach A.M., Leeser D.B.,Wang H., Tadaki D.K., Fernandez C., Destephano D., Hale D., Kirk A.D., Gage F.A., Elstere A. 2009. Assessment of cadaveric organ

viability during pulsatile perfusion using infrared imaging. Transplantation 87(8): 1163–6

- Gorbach A.M., Wang H., Dhanani N.N., Gage F.A., Pinto P.A., Smith P.D., Kirk A.D, Elster E.A. 2008. Assessment of critical renal ischemia with real-time infrared imaging. J Surg Res 149(2): 310–8.

- Haller H, Ito S, Izzo JL Jr, et al.; ROADMAP Trial Investigators. Olmesartan for the delay or prevention of microalbuminuria in type 2 diabetes. N Engl J Med 2011; 364:907–917.

- Hansen HP, Tauber-Lassen E, Jensen BR, Parving HH. Effect of dietary protein restriction on prognosis in patients with diabetic nephropathy. Kidney Int 2002; 62:220–228.

- Harding J, Wertheim D, Williams R, Melhuish J, Banerjee D, Harding K. Infrared imaging in diabetic foot ulceration. Proceedings of the Annual International Conference of the IEEE, Engineering in Medicine and Biology Society; 1998; Hong Kong.

- Hassan, M., et al., Quantitative Assessment of Tumor Vasculature and Response to Therapy in Kaposi's Sarcoma Using Functional Noninvasive Imaging, Technology in Cancer Research and Treatment, 3, 451–457, Adenine Press, 2004.

- Henke, S., Karstädt, D., Möllmann, K.-P., Pinno F. and Vollmer M. Identification and suppression of thermal reflections in infrared thermal imaging. University of Applied Sciences, Brandenburg, Germany. InfraMation 2004, Proceedings Volume 5, 287-298 (2004)

- HGH. Infrared camera for thermography IRCAM 82. 2005

- Hobizal K. B., Wukich D. K. Diabetic foot infections: current concept review. Diabetic Foot & Ankle 2012, 3: 18409 - http://dx.doi.org/10.3402/dfa.v3i0.18409.

- Hoeldtke, R.D.; Bryner, K.D.; Horvath, G.G.; Phares, R.W.; Broy, L.F.; Hobbs, G.R. Redistribution of sudomotor response is an early sign of sympathetic dysfunction in type 1 diabetes, Diabetes 50 (2001) 436–443.

- Horn, B. Closed-form solution of absolute orientation using unit quaternions. Reprinted from Journal of the Optical Society of America A, Vol. 4, page 629, April 1987

- Houdas, Y. Ring, E.F.J. Human Body Temperature—Its Measurement and Regulation, Plenum Press, New York, 1982.

- http://www.guideline.gov/content.aspx?id=34831&search=diabetic+foot+disorders%3a+a+clinical+practice+guideline (Accessed 27 December 2012).

- Huygen F.J., Niehof S., Klein J., Zijlstra F.J. 2004. Computer-assisted skin videothermography is a highly sensitive quality tool in the diagnosis and monitoring of complex regional pain syndrome type I. Eur J Appl Physiol 91(5–6): 516–524

- IDF, International Diabetes Federation. Time To Act: Diabetes And Foot Care. Brussels: International Diabetes Federation; 2005.

- IACT, International Academy of Clinical Thermology. Standards and Protocols in Clinical Thermographic Imaging. September 2002.

- Ismail-Beigi F, Craven T, Banerji MA, et al.; ACCORD trial group. Effect of intensive treatment of hyperglycaemia on microvascular outcomes in type 2 diabetes: an analysis of the ACCORD randomised trial. Lancet 2010; 376:419–430.

- Jones B, Plassmann P. Digital infrared thermal imaging of human skin. IEEE Eng Med Biol Mag 2002;21:41-8.

- Jones C, Ring E, Plassmann P, Ammer K, Wiecek B. Standardisation of infrared imaging: a reference atlas for clinical thermography—initial results. Thermology International 2005; 15:157-8.

- Keech A, Simes RJ, Barter P, et al.; FIELD study investigators. Effects of long-term fenofibrate therapy on cardiovascular events in 9795 people with type 2 diabetes mellitus (the FIELD study): randomized controlled trial. Lancet 2005;366:1849–1861.

- Keen H.I., Mease P.J., Bingham III C.O. et al. 2011. Systematic review of MRI, ultrasound, and scintigraphy as outcome measures for structural pathology in interventional therapeutic studies of Knee osteoarthritis: Focus on Responsiveness. J Rheumatol 38: 142–154.

- Keith, L.G., Oleszczuk, J.J., Laguens, M. Circadian rhythm chaos: A new breast cancer marker, Int. J. Fertil. Women Med. 46 (6) (2001) 238–247.

- Keyserlingk, J.R.; Ahlgren, P.D.; Yu, E.; Belliveau, N. Infrared imaging of breast: Initial reappraisal using high-resolution digital technology in 100 successive cases of stage I and II breast cancer, The Breast Journal 4 (4) (1998) 241–251.

- Keyserlingk, J.R., Ahlgren, P.D., Yu, E., Belliveau, N., Yassa, M. Functional infrared imaging of the breast: Historical perspectives, current application and future considerations, in: Biomedical Engineering Handbook, CRC Press, 2006 (Chapters 26-1 to 26-30).

- Kimura, J., Principles and variations of nerve conduction studies, in: Electrodiagnosis in Diseases of Nerve and Muscle: Principles and Practice, Oxford University Press, New York, 2001, pp. 91–129.

- Klausen K, Borch-Johnsen K, Feldt-Rasmussen B, et al. Very low levels of microalbuminuria are associated with increased risk of coronary heart disease and

death independently of renal function, hypertension, and diabetes. Circulation 2004;110:32–35.

- Lavery L, Armstrong D, Harkless L. Classification of Diabetic Foot Wounds. The Journal of Foot and Ankle Surgery 35(6):528-531 , 1996.

- Lavery L, Higgins K, Lactot D, Constantinitides G, Zamorano R, Armstrong D, et al. Home monitoring of foot skin temperatures to prrevent ulceration. Diabetes Care 2004;27:2642-7.

- Lavery LA, Armstrong DG, Murdoch DP, Peters EJ, Lipsky BA. Validation of the Infectious Diseases Society of America's diabetic foot infection classification system. Clin Infect Dis 2007; 44: 562_5.

- Lavery LA, Higgins KR, Lanctot DR et al. Preventing diabetic foot ulcer recurrence in high-risk patients: use of temperature monitoring as a self-assessment tool. Diabetes Care 30 (1), 14–20 (2007).

- Lawson, R.N.; Chughtai, M.S. Breast cancer and body temperatures, Can. Med. Assoc. J. 88 (1963) 68–70.

- Lipsky BA, Berendt AR, Deery HG, Embil JM, Joseph WS, Karchmer AW, et al. Infectious Diseases Society of America. Diagnosis and treatment of diabetic foot infections. Clin Infect Dis 2004; 39: 885_910.

- Litzelman, D.K.; Marriott, D.J.; Vinicor, F. Independent physiological predictors of foot lesions in patients with NIDDM, Diabetes Care 20 (1997) 1273–1278.

- Manichand Healthcare www.manichand-healthcare.com/inhoud/Product1.htm (Accessed 5 December 2009) http://www.syntens.nl/innovatietop100/top-100-2010/Nummer-24.aspx (accessed January 2013)

- Mannara, G.; Salvatori, G.C.; Pizzuti, G.P. Ethyl alcohol induced skin temperature changes evaluated by thermography: Preliminary results, Boll. Soc. Ital. Biol. Sper. 69 (10) (1993) 587–594.

- Mauer M, Zinman B, Gardiner R, et al. Renal and retinal effects of enalapril and losartan in type 1 diabetes. N Engl J Med 2009;361:40–51.

- Merla A, Di Donato L, Di Luzio S, Farina G, Pisarri S, Proietti M, et al. Infrared functional imaging applied to Raynaud phenomenon. IEEE Eng Med Biol Mag 2002;21(6):73-9.

- MINSA, Ministerio de Salud. Oficina General de Epidemiología. Análisis de la Situación - Perú. 2004.

- Moghissi ES, Korytkowski MT, DiNardo M, Einhorn D, Hellman R, Hirsch IB, Inzucchi SE, Ismail-Beigi F, Kirkman MS, Umpierrez GE 2009 American Association

of Clinical Endocrinologists and American Diabetes Association consensus statement on inpatient glycemic control. Diabetes Care 32:1119–1131.

- Moghissi ES, Korytkowski MT, DiNardo M, Einhorn D, Hellman R, Hirsch IB, Inzucchi SE, Ismail-Beigi F, Kirkman MS, Umpierrez GE 2009 American Association of Clinical Endocrinologists and American Diabetes Association consensus statement on inpatient glycemic control. Endocr Pract 15:353–369.

- Murff RT, Armstrong DG, Lanctot D, Lavery LA, Athanasiou KA. How effective is manual palpation in detecting subtle temperature differences? Clin. Podiatr. Med. Surg. 15(1), 151–154 (1998).

- Murff RT, Armstrong DG, Lanctot D, Lavery LA, Athanasiou KA. How effective is manual palpation in detecting subtle temperature differences? Clin. Podiatr. Med. Surg. 15(1), 151–154 (1998).

- Murphy L., Schwartz T.A, Helmick C.G et al. 2008. Lifetime risk of symptomatic knee osteoarthritis. Arthritis & Rheumatism 59 (9): 1207–1213

- Nagase T., Sanada H., Takehara K., Oe M., Iizaka S., Ohashi Y., Oba M., Kadowaki T., Nakagami G. Variations of plantar thermographic patterns in normal controls and non-ulcer diabetic patients: Novel classification using angiosome concept. Journal of Plastic, Reconstructive & Aesthetic Surgery (2011) 64, 860 − 866.

- Neyra, L.; Solís, J.; Castillo, O.; García, F. Diabetic foot. Rev Soc Peru Med Interna 2012; vol 25 (2). Page 76-88.

- Ng, E.Y.-K. A review of thermography as promising non-invasive detection modality for breast tumor. Adjunct NUH Scientist, Office of Biomedical Research, National University Hospital of Singapore, Singapore. International Journal of Thermal Sciences 48 (2009) 849–859.

- Ng, E.Y.-K. Is thermal scanner losing its bite in mass screening of fever due to SARS? Medical Physics 32 (1) (2005) 93–97.

- Ng, E.Y.-K. Sudharsan, N.M. Effect of blood flow, tumour and cold stress in a female breast: A novel time-accurate computer simulation, International Journal of Engineering in Medicine 215 (H4) (2001) 393–404.

- Ng, E.Y.-K.; Sudharsan, N.M. Numerical modelling in conjunction with thermography as an adjunct tool for breast tumour detection, BMC Cancer 4 (17) (2004) 1–26.

- Ngan, A., Durand F. and Matusik W. Experimental Analysis of BRDF Models. Eurographics Symposium on Rendering (2005). Kavita Bala, Philip Dutré (Editors)

- NGC National Guideline Clearinghouse. Diabetic foot Problems. Inpatient management of diabetic foot problems. National Institute for Health and Clinical Excellence (NICE); 2011.

- NICE Clinical Guidelines 119. Diabetic Foot Problems: Inpatient Management of Diabetic Foot Problems. National Institute for Health and Clinical Excellence. NICE 2012.

- Ogawa H, Nakayama M, Morimoto T, et al.; Japanese Primary Prevention of Atherosclerosis With Aspirin for Diabetes (JPAD) Trial Investigators. Low dose aspirin for primary prevention of atherosclerotic events in patients with type 2 diabetes: a randomized controlled trial. JAMA 2008;300:2134–2141.

- Oyibo SO, Jude EB, Tarawneh I, Nguyen HC, Harkless LB, Boulton AJ. A comparison of two diabetic foot ulcer classification systems: the Wagner and the University of Texas wound classification systems. Diabetes Care 2001; 24: 84_8.

- Papanas N, Papatheodorou K, Papazoglou D, Monastiriotis C, Maltezos E. Foot temperature in Type 2 diabetic patients with or without peripheral neuropathy. Exp. Clin. Endocrinol. Diabetes 117(1), 44–47 (2009).

- Parisky Y.R., Sardi A, Hamm R. et al. 2003 Efficacy of computerized infrared imaging analysis to evaluate mammographically suspicious lesions. AJR Am J Roentgenol 180 (1): 263–269

- Parving HH, Persson F, Lewis JB, Lewis EJ, Hollenberg NK; AVOID Study Investigators. Aliskiren combined with losartan in type 2 diabetes and nephropathy. N Engl J Med 2008;358: 2433–2446.

- Pascoe D, Mercer J B, De Weerd L. Physiology of Thermal Signals. In: The Biomedical Engineering Handbook, 3rd. edition; Medical Devices and Systems, CRC press, New York, 2006, Chapter 21, p 1–20.

- Plassmann, P.; and Ring, E.F.J. "An open system for the acquisition and evaluation of medical thermological images," Eur. J. Thermology, vol. 7, no. 4, pp. 216-220, 1997.

- Poljak-Blazi, M., Kolari D., Jaganjac M., Zarkovi K., Skala K., Zarkovic N. 2009. Specific thermographic changes during Walker 256 carcinoma development: differential infrared imaging of tumour, inflammation and haematoma. Cancer Detection and Prevention, Volume 32, Issue 2, 2009.

- Pyõrãlä K, Pedersen TR, Kjekshus J, Faergeman O, Olsson AG, Thorgeirsson G. Cholesterol lowering with simvastatin improves prognosis of diabetic patients with coronary heart disease. A subgroup analysis of the Scandinavian Simvastatin Survival Study (4S). Diabetes Care 1997; 20:614–620.

- Qi, H.; Kuruganti, P.T.; Snyder, W.E. Detecting breast cancer from thermal infrared images by asymmetry analysis, in: Biomedical Engineering Handbook, CRC Press, 2006 (Chapters 27-1 to 27-14).

- Ring, E.F.J. Quantitative thermal imaging, Clin. Phys. Physiol. Meas. 11 (1990) 87–95.

- Ring, E.F.J.; Ammer, K. The technique of infrared imaging in medicine, Thermology International 10 (1) (2000) 7–14.

- Roback K, Johansson M, Starkhammar A. Feasibility of a thermographic method for early detection of foot disorders in diabetes. Diabetes Technol. Ther. 11(10), 663–667 (2009).

- Roback K. An overview of temperature monitoring devices for early detection of diabetic foot disorders. Expert Rev. Med. Devices 7(5), 711–718 (2010).

- Scognamiglio R, Negut C, Ramondo A, Tiengo A, Avogaro A. Detection of coronary artery disease in asymptomatic patients with type 2 diabetes mellitus. J Am Coll Cardiol 2006;47:65–71.

- Seibel, J. Diabetes Overview. WebMD Public Information from the U.S. Department of Health and Human Services. http://diabetes.webmd.com/diabetes-overview. 2008.

- Sever PS, Poulter NR, Dahlöf B, et al. Reduction in cardiovascular events with atorvastatin in 2,532 patients with type 2 diabetes: Anglo-Scandinavian Cardiac Outcomes Trialdlipid-lowering arm (ASCOT-LLA). Diabetes Care 2005;28: 1151–1157

- Shepherd J, Barter P, Carmena R, et al. Effect of lowering LDL cholesterol substantially below currently recommended levels in patients with coronary heart disease and diabetes: the Treating to New Targets (TNT) study. Diabetes Care 2006;29:1220–1226.

- Singh IM, Shishehbor MH, Ansell BJ. High-density lipoprotein as a therapeutic target: a systematic review. JAMA 2007; 298:786–798.

- Skala, T.; Kolari, D.; Dujmovi, A. Extremities Perfusion Stimulation and Dynamic Evaluation by Thermography Analyses. Periodicum Biologorum VOL. 112, No 4, 475–478, 2010. ISSN 0031-5362.

- Spalding S.J., Kwoh C.K., Boudreaur R. et al. 2008. Three-dimensional and thermal surface imaging produces reliable measures of joint shape and temperature: a potential tool for quantifying arthritis. Arthritis Research & Therapy 10 (1)

- Spallone V, Bellavere F, Scionti L, et al.; Diabetic Neuropathy Study Group of the Italian Society of Diabetology. Recommendations for the use of cardiovascular tests in

diagnosing diabetic autonomic neuropathy. Nutr Metab Cardiovasc Dis 2011; 21:69–78.

- Springett, K.; White, R.J. Skin changes in the at risk foot and their treatment, Br. J. Community Nurs. 12 (2002) 25–32.

- Standards Technical Reference (STR 2003) for Thermal Imagers for Human Temperature Screening. Part 1: Requirements and Test Methods. TR 15-1, Spring Singapore, ISBN 9971-67-963-9.

- Steiner G., Sobottka S.B., Koche et al. 2011. Intraoperative imaging of cortical cerebral perfusion by time-resolved thermography and multivariate data analysis. J Biomed Optics 16(1): 016001

- Sun PC, Lin HD, Jao SH, Ku YC, Chan RC, Cheng CK. Relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet. Diabetes Res. Clin. Pract. 73(1), 41–46 (2006).

- Sun, P.C.; Jao, S.H.; Cheng, C.K. Assessing foot temperature using infrared thermography, Foot Ankle Int. 26 (2006) 847–853.

- Szentkuti A.; Skala Kavanagh H.; Grazio S. Infrared Thermography and Image Analysis for Biomedical Use. Periodicum Biologorum. Vol. 113, No 4, 385–392, 2011. ISSN 0031-5362.

- Torres H. L.; Gutiérrez, C.; Pajuelo, J.; Pando, R.; Arbañil, H. Clinical and epidemiological characteristics of patients hospitalized for diabetic foot in Hospital Nacional Dos de Mayo, Lima-Peru. Revista Peruana de Epidemiología ISSN 1609-7211. Rev. Peru. Epidemiol. Vol 16 N° 3 December 2012.

- Vinik AI, Maser RE, Mitchell BD, Freeman R. Diabetic autonomic neuropathy. Diabetes Care 2003; 26:1553–1579.

- Wagner FW, Jr. The dysvascular foot: a system for diagnosis and treatment. Foot Ankle 1981; 2: 64 - 122.

- Wang H, Wade D, Kam J. IR imaging of blood circulation of patients with vascular disease. Proceedings of Thermosense. XXVI; 2004 Apr 13-15; Bellingham, WA.

- Wang, S.C., The Singapore national breast screening programme: Principles and implementation, Ann. Acad.Med. Singapore 32 (2003) 466–476.

- Watkins, P.J. The diabetic foot, BMJ 326 (2003) 977–979.

- Wiecek, B.; Zwolenik, S.; Jung, A.; Zuber, J. "Advanced thermal and radiological image processing for clinical diagnostics," in Proc. 1st Joint IEEE BMES/EMBS Conference, Atlanta, GA, 13-16 October, 1999.

- Wile, DJ, Toth C. Association of metformin, elevated homocysteine, and methylmalonic acid levels and clinically worsened diabetic peripheral neuropathy. Diabetes Care 2010; 33:156–161.

- Yang, Y., Huang, S. Image segmentation by fuzzy c-means Clustering algorithm with a novel penalty term. Computing and Informatics, Vol. 26, 2007, 17–31

- Yu, C., Seo Y. and Lee, S.W. Global optimization for estimating a BRDF with multiple specular lobes. Proc. CVPR, pages 319–326, 2010.

- Zgur, T.; Vodusek, D.B.; Krzan, M.; Vrtovec, M.; Denislic, M.; Sibanc, B. Autonomic system dysfunction in moderate diabetic polyneuropathy assessed by sympathetic skin response and Valsalva index, Electromyogr. Clin. Neurophysiol. 33 (1993). 433–439.

Abstract:

The object of the thesis is to analyze the potential of thermography in the early diagnosis of type 2 diabetic foot. The main advantages of thermography are that it is simple to use, non-invasive, contactless, non-irradiant, and fast.

A robust acquisition protocol is proposed, as well as a dedicated image processing algorithm. The algorithm includes a pre-processing step, plus a segmentation and a rigid registration procedures. Various parameters are assessed: the mean and standard deviation of right and left feet plantar surfaces temperaure, as well as the percentage of pixels such that the absolute point to point temperature difference between right and left feet is greater than 2.2°C. A percentage greater than 1% indicates significative hyperthermia regions.

A transversal clinical study is conducted on a population of 85 persons of type 2 diabetic foot. They are classified in one of these three groups: Low risk, Medium risk, and High risk. For the Low risk group, the mean temperature is close to 32°C. For the medium one, it goes down to 31°C, and increases for the High risk group to a value of 32°C. In the early stage of diabetic foot, *i.e.* from the Low risk group to Medium risk group, the plantar foot surface temperature is lowered by 1°C: if this result is confirmed by other clinical tests, this information can be useful for the early diagnosis of diabetic foot. Finally, 9 images out of the 85 show hyperthermia, mainly in the heel or toes regions. This hyperthermia indication may be of a substantial assistance in the early prevention of foot ulcer and can help in avoiding subsequent foot amputation.

Résumé :

L'objectif de cette thèse est d'analyser l'utilité de la thermographie dans le cadre du diagnostic précoce du pied diabétique. Un protocole d'acquisition robuste des images thermiques est proposé, ainsi qu'un algorithme spécifique de traitement de ces images. Cet algorithme comporte une étape de prétraitement, suivie d'une segmentation et d'un recalage rigide. Différents paramètres sont ensuite évalués : la moyenne et l'écart type de la température de la voute plantaire de chacun des pieds droit et gauche, de même que le pourcentage des pixels pour lesquels la différence de température entre les pieds droit et gauche est supérieure à 2,2°C. Cela permet de mettre en évidence les régions en hyperthermie.

Une étude clinique est menée sur une population de 85 personnes diabétiques. Ces patients sont classés sur critères médicaux dans trois groupes : risque faible, moyen ou élevé. Pour le groupe à faible risque, la température des pieds est proche de 32°C. Pour le groupe à risque moyen, elle descend à 31°C et remonte à 32°C pour le groupe risque élevé. Au stade précoce du pied diabétique, c'est-à-dire entre le risque faible et le risque moyen, la température de la surface plantaire diminue de 1°C : si ce résultat est confirmé par d'autres essais cliniques, cette information peut être utile pour le diagnostic précoce du pied diabétique. Enfin, 9 images sur les 85 étudiées révèlent une hyperthermie significative : cette indication d'hyperthermie peut être d'une aide considérable dans la prévention précoce de l'ulcère du pied et pourrait éviter des complications graves chez ces patients.