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Pressure Sore Etiology - Highlighted with Optical Measurements of the Blood Flow

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Abstract

In line with the quality awareness of good prevention of pressure sores and in treatment of those sores already developed, evaluation of antidecubitus mattresses plays an important role. However, there are shortages in the evaluations performed today, since often interface pressure is the only parameter regarded. Since ischaemia in the tissue is the primary cause of pressure sore, the focus in this thesis is on blood flow measurements in tissue exposed external loading. To study the tissue blood flow would give a better and more direct indication on the mattress effectiveness in minimizing the negative effects on the tissue viability.

The results presented in this thesis reveal that the superficial blood flow in areas prone to pressure sore development, is affected by increased skin temperature and external loading of the tissue. Both the effects from pressure and shear stress have been studied.

Measurements of the tissue blood flow is interesting to relate to the two theories about at which tissue layer the pressure sores start to develop. To achieved more knowledge about the pressure sore etiology and also be able to non-invasively measure the tissue blood flow for evaluations of antidecubitus mattresses an optical sensor has been developed. The sensor combines the two optical methods, laser Doppler flowmetry and photoplethysmography. With the design of the sensor, measurements of the superficial skin blood flow and the deeper blood flow, even the muscle blood flow, can be performed. Measurement depths of 2 mm, 8 mm, and 20 mm into the tissue is assumed.

Preliminary result from measurements performed with the optical sensor in four test subjects, revealed great individual differences in blood flow, but also different response to the same external loading at different measurement depths, in the same individual. This new optical sensor is likely to be of great value in future studies of pressure sore etiology and in future evaluations of antidecubitus mattresses.

Swedish summary - Sammanfattning

I arbetet med att förebygga trycksår och i behandlingen av redan uppkomna sår utgör utvärderingar av så kallade trycksårsmadrasser en viktig del. Idag är dock antalet utvärderingar få och de som genomförs baseras till stor del på studier av madrassens tryck mot vävnaden och madrassens förmåga att fördela trycket bättre.

Eftersom blodbrist i vävnaden, ischemi, är den primära orsaken till trycksår, föreslås i den här avhandlingen att större vikt bör läggas vid mätning av blodflödet i vävnaden i kontakt med madrassen. Detta skulle leda till bättre utvärderingar av madrassens egenskaper då madrassens påverkan på blodflödet kan ses.

Studierna som presenteras i den här avhandlingen visar på effekterna på det ytliga blodflödet vid ökning av hudtemperaturen och vid extern belastning av huden. Effekterna på blodflödet från både tryck och skjuvkrafter har studerats.

Mätningar av blodflödet är intressenta att relatera till de två teorierna om på vilket djup i vävnaden trycksår uppkommer. För att vidare kunna studera hur trycksår uppkommer och i förlängningen utvärdera trycksårsmadrasser, har en optisk sensor utvecklats. Sensorn kombinerar två icke-invasiva metoder för blodflödesmätning, laser Doppler teknik och fotopletysmografi. Genom att designa sensorn för det specifika mätområdet kan det ytliga och djupa blodflödet mätas. De tre mätdjupen med sensorn uppskattas till 2 mm, 8 mm och 20 mm.

De preliminära resultaten från mätningar med den optiska sensorn visar på stora individuella skillnader och att blodflödet på olika vävnadsdjup reagerar olika på samma extern belastning hos en och samma individ. Det är troligt att användandet av den här sensor kan ge en ökad förståelse kring uppkomsten av trycksår och i framtiden användas för utvärdering av trycksårsmadrasser.

Contents

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Mum and Dad - thank you for the constant encouragement and support in everything I do. Thank you for always believing in me.

Kim - thank you for your love, support, and the red flower! And for forcing me to cool down when I need it.

Easter Sunday 2006

Annika Jonsson

List of papers

Paper I

Evaluation of antidecubitus mattresses.
A. Jonsson, M. Lindén, M. Lindgren, L.-Å. Malmqvist, Y. Bäcklund
Medical & Biological Engineering & Computing, 2005, 43(5): 541-547
Reprinted with permission from the IFMBE

Paper II

Skin temperature effects on the skin blood flow at areas prone to pressure sore development.
A. Jonsson, M. Lindgren, M. Lindén
Conference proceeding at the Nordic Baltic Biomedical Conference, NBC'05, 13-17 June 2005, Umeå, Sweden.
Reprinted with permission from the IFMBE.

Paper III

Peripheral circulatory response to shear stress applied to the sacral region.
L. Klevbo, A. Jonsson, N. Ford
Submitted

Paper IV

New sensor design made to discriminate between tissue blood flow at different tissue depths at the sacral area.
A. Jonsson
Technical report, Department of Computer Science and Electronics,
Mälardalen University.

Author's contribution

Paper I

The author has initiated the paper, done the background research, and written the paper.

Paper II

The author is responsible for planning the study, performing the measurements, analyzing the results and writing the paper.

Paper III

The author has initiated the study, performed the measurements, and written of the paper.

Paper IV

The author has been involved in the designing, development and testing of the optical probe. The author has also written the paper.

Chapter 1

Introduction

Pressure sores are common problems in today's health care. A pressure sore leads to physiological as well as psychological suffering for the individual affected. The cost for the society, associated with prevention and treatment of pressure sores, is considerable. Today, the use of specially designed mattresses, so called antidecubitus mattresses for prevention and as a step in the treatment of pressure sores, is common and accepted. But do they fulfill their promises?

The problem is that no consensus about what parameters to regard when evaluating or standardized methods for measuring these parameters exist. The lack of evaluation of antidecubitus mattresses makes it troublesome for health care personnel to make well-founded decisions about purchase and ordination of antidecubitus mattresses.

Chapter 2

Pressure sores

Decubitus ulcers, ischemic ulcers, bedsores, and pressure sores are all names for the same problematic wound. The definition of a pressure sore is an area of tissue damage appearing after a prolonged period of ischaemia in the tissue [54].

Impaired persons that are subjected to longer periods of immobility, for example, elderly [65, 97], amputated [92], patients with hip fracture [99], and spinal cord injured [69] are at high risk of developing pressure sores. The number of patients at risk for pressure sore development is increasing due to an increased length of life and advances in medicine. In addition, paralyzed persons today live a more normal and active life, implying an increased time spent sitting in a wheelchair. The cost associated with prevention and treatment of pressure sores is considerable [66, 89].

Functions and properties of the tissue

The skin is a major sense organ with the functions to protect, retard water from the deeper tissue, regulate the body temperature, and excrete small quantities of waste substances [98]. The soft tissue overlying the bone constitutes of inter alia, the tissue layers; stratum corneum, epidermis, dermis, subcutaneous fat, and muscle, Figure 2.1.

The two most superficial tissue layers, which constitute the skin, are the epidermis and dermis. The epidermis is non-vascular and mainly there for protection.

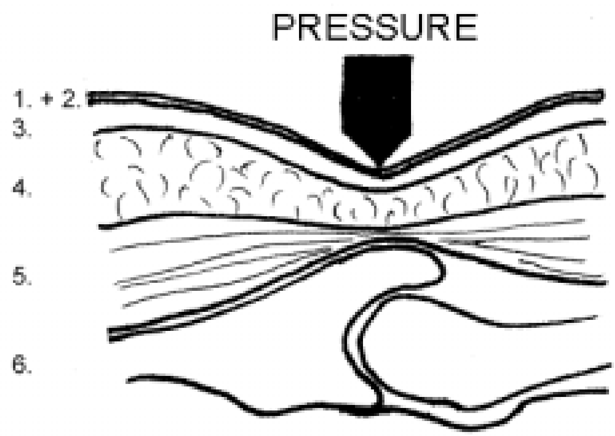

Figure 2.1: The tissue layers: 1. Stratum corneum 2. Epidermis 3. Dermis 4. Subcutaneous fat 5. Muscle 6. Bone.

Epidermis is especially thick at the hand and foot, areas that are often stressed. The dermis, on the other hand, contains blood vessels. The subcutaneous fat envelops the body and gives contour and shape. Large individual differences and differences between body regions for the same individual can be seen in the thickness of this layer. The subcutaneous layer lacks significant tensile strength and is vulnerable to mechanical forces [91]. The muscle has good pressure distributing properties [75] but animal studies have shown that the subcutaneous tissue and especially the muscle is more susceptible to pressure induced injury than the epidermis [24, 75]. This can to some extent be explained by the fact that the muscle has a higher metabolism.

When pressure is applied, the tissue layers are compressed to different extent depending on the properties of the layer. The collagen content makes the subcutaneous fat relatively resistant to mechanical forces and less susceptible to compression of the vascularies [91]. Ageing leads to decreased collagen content of the dermis and the collagen and elastic fibers becomes more haphazardly structured [78], thus the resistance to mechanical forces decreases with age. Other ageing effects are decreased skin microcirculation [81], decreased moisture content in the stratum corneum [78], increased propensity for blistering and/or erosion following shear forces [78], and decreased wound healing rate [26, 98].

Factors in pressure sore etiology

The interface between the body and a support surface is characterized by peak pressure and pressure gradient that together with the tissue's mechanical nature, result in internal stresses and strains. These stresses and strains might be sufficient to impair the local blood flow and lymphatic flow, if the flexible walls of the blood and lymph vessels collapse. This impaired circulation, can if prolonged, lead to ischaemia that involves impaired transport of nutrients and waste products to and from the cells.

The etiology of pressure sores is not fully understood. A major question that still remains is at which tissue depth pressure sores start to develop. There are two theories about this development. One of the theories is that the initial pathologic changes occur in the deep muscle and progress upwards, so called bottom-to-top sore formation [24, 82]. The other theory is that the sore formation first begins in the epidermis and upper dermis and then progresses down if the pressure is not relieved, known as top-to-bottom sore formation [16, 103]. However, the scale used to grade pressure sores in Europe is based on the assumption that the sore is first observed in the epidermis and develope downwards [32].

For persons that spend most of their time seated in a wheelchair, the ischial tuberosities are the most frequently locations for sore development and for persons confined to bed, the sacrum and heels dominate. Other common places are the back of the head, the shoulder, the hip, and at tissue areas in contact with plaster and orthopedic devices, such as prostheses. Interface pressure measurements in individuals lying in bed, showed higher pressure values under the sacral area than under the buttock, and with the head end of the bed elevated, the pressure values under buttock were higher then at the sacral area [2]. The sacral area has shown to have a significantly lower mean baseline blood flow compared to the forearm and gluteus maximus in both healthy persons and paraplegic persons [48]. In addition, the sacral area show a more unstable blood flow response, poorer regulation of the microcirculation, to external loading than the gluteus maximus [87].

The factors contributing to the formation of pressure sores are several and can be divided into two groups, extrinsic and intrinsic. Extrinsic factors are factors acting from outside of the body and that directly influence the risk of developing pressure sore [15]. The extrinsic factors are externally applied pressure, shear stress and a non-favourable microclimate i.e. increase in skin temperature and humidity. The intrinsic factors consider the individuals condition, and are for example, grade of immobility and activity [65], age [13, 43, 65], nutrient intake [19, 101], skin condition [1, 78], loss of sensation [52], incontinence [28, 67], low blood pressure [13, 65, 69, 86], general physical condition [27] and bodily constitution [3].

This thesis focuses on the extrinsic factors and primarily their influences on the tissue blood flow.

Pressure and shear

Externally applied pressure is suggested to be the primary cause to tissue ischaemia [25, 33, 58] and the amount of damage is increasing with the magnitude of the loading and application time [54]. Due to the tissue's inhomogeneous structure, external loading creates different amounts of pressure inside the tissue. Different pressure levels in different tissue layers have been shown and also that the pressure near the bony prominence can be as high as five times the externally applied pressure [58].

There is no consensus about which pressure level that will cause tissue damage but loading in the range of the blood pressure inside the capillaries will impair the blood flow [54]. The pressure level required to impair or occlude the blood flow is very individual and depends on the individual's general condition and at which tissue area that loading is applied [7, 20, 29, 55, 87]. In geriatric patients, application of low pressure in the range of 11-50 mmHg has shown to impair the blood flow in the tissue over sacrum and gluteus maximus [10, 29].

During external loading of the tissue, at lower magnitude than the diastolic blood pressure (approx. 60 mmHg) the local venous and arteriolar blood pressure might respond with autoregulation and increase. At loading of pressures in the range of 60 mmHg the arteriolar pressure have been shown to stabilize 10 mmHg above the applied pressure [56]. Experimentally this has been shown through increased skin blood flow in healthy individuals when low levels of external pressure were applied,

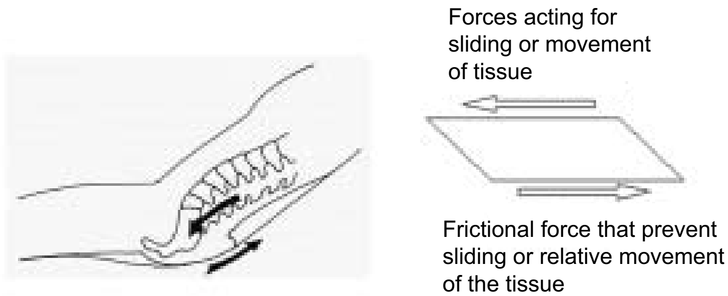

Figure 2.2: Parallel shear stress for example when the person is in recumbent position in bed (After [31]).

this irrespective of the persons age [35, 46, 76, 105] and with an inconsistent response pattern in elderly patients at risk of pressure sores [36]. In one study performed, the skin blood flow over sacrum increased in elderly patients without risk of developing pressure sores, and decreased in elderly patients at high risk of developing pressure sores when the individuals were placed in supine position [88].

Shear stresses are always present when the external force at the tissue is not exclusively perpendicular to the tissue [9]. The deformation of the tissue is due to the stress applied, which constitutes of compressive stress (pure pressure), and shear stress [17, 42]. The presence of shear stress is obvious when the individual is lying in bed with the head end elevated and the body has a tendency to slide against the lower end of the bed, Figure 2.2. Studies have shown that shear stress is at least as important as applied pressure in the development of pressure sores and that the severity of tissue injury increases with the amount of shear stress [6, 9, 41]. Levine and Kett [62] have explained the deformation of the tissue as a measure of the net effect of the externally applied load and claim that tissue blood flow is closer related to tissue deformation than externally applied pressure [52].

Bennett [8] discussed two types of stress: pinch shear stress and parallel shear stress, Figure 2.2 and Figure 2.3. Pinch shear stress occurs when the pressure distri-

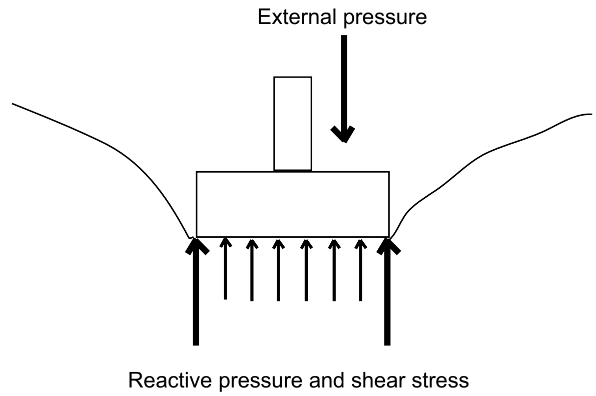

Figure 2.3: External loading at an uneven surface leading to pinch shear stresses.

bution is uneven and pressure gradients occur, for example around bony prominences or at the brims of an orthopedic device. Parallel shear stress occurs due to frictional forces when two forces act in opposing direction, but not in the same level. This leads to tissue deformation. Due to the increased pressure value inside the tissue [58] and that shear stress exist where pressure gradient occur, the total stress is maximized at bumpy areas in the vicinity of muscles and bones, for example at a bony prominence or at the brim of orthopedic devices [8], Figure 2.4.

Forces that causes shear stress can be said to act parallel to the skin [9] and affect the tissue perfusion by stretching the skin in relation to underlying structures and damage the vascular structure. The effect on the skin vasculature and microcirculation from shear stress and shear stress in combination with pressure have been reported by several researchers [6, 9, 12, 104, 106].

During ischaemia, the cells continue their metabolism, producing toxic metabolic bi-products that are accumulated locally in the tissue. This accumulation increases the rate of cell death compared to a non-ischaemic situation. Following relief of external loading, healthy tissue will experience reactive hyperaemia if a period of

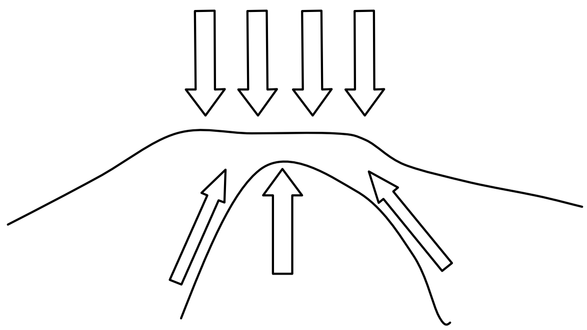

Figure 2.4: Internal tissue stresses over bony prominence.

ischaemia has occurred. The purpose of reactive hyperaemia is to compensate for the impaired blood flow during loading and remove toxic materials and restore the nutritional balance in the cells in the effected tissue area [91]. The magnitude and duration of the reactive hyperaemia depend on the tissue condition, and the magnitude of the external loading and its duration [44, 48, 70], and also if the skin has been previously stressed [46]. The result from one study performed with rats, indicates that the magnitude of the reactive hyperaemia increases in heated skin compared to unheated skin [76].

How the reactive hyperaemia response is affected by age and impaired health is not clear. In elderly and debilitated persons, an impaired and delayed tissue recovery compared to in younger persons has been assessed with laser Doppler techniques and with transcutaneous oxygen tension [5, 44]. Whereas Springle et al. [93] found no difference in reactive hyperaemia magnitude between diabetic amputees and healthy individuals, but a lower magnitude was seen in the test subjects who smoked.

The cutaneous blood flow is centrally and locally regulated and an increased body temperature or skin temperature leads to dilatation of the vessels [60]. Besides the body's own regulation of the temperature, the surrounding climate affect the skin temperature and thereby also the skin blood flow [50]. It has been shown that elderly and impaired persons have an impaired ability to respond to heating of the skin with an increased skin blood flow [30]. This possibly contributes to increase the risk of developing pressure sores at small increases in, both local and central body temperature.

Temperature and humidity

The third extrinsic factor is related to bed condition. Resting in bed leads to changes in tissue temperature and humidity, which affects the cutaneous blood flow and the skin's resistance to external loading. Increased tissue temperature leads to an increased metabolism in the tissue which increases the tissue's demand of nutrition and oxygen [98]. Therefore tissue that already suffers from poor circulation due to external loading and is exposed to increased temperature, will suffer an even larger deficit of blood flow. It has also been shown that the severity of pressure-induced tissue injuries correlates with an increase in applied temperature when applying the same amount of pressure [53].

Depending on the type of mattresses or wheelchair cushion, the skin temperature might increase or decrease. Foam, viscoelastic foam, and latex rubber support surfaces gives an increased skin temperature accompanied by a reduction in heat flux leading to accumulated heat [22, 34, 90, 95]. On the other hand, air-loss mattresses [77] and gel mattresses/cushions [22, 90] might lower the skin temperature, causing a vasoconstrictor response and decrease of the blood supply to the tissue [71]. The result from another study [95] showed unchanged skin temperature and an increased heat flux with gel cushions and a decreased skin temperature and an increased heat flux with water cushions. An interesting finding is that spinal cord injured had a significantly higher skin temperature than able-bodied individuals, regardless of the cushion type they were seated on [90].

Humidity can lead to skin damage by abrasion [21] and the factors contributing to increased humidity are perspiration and urine and fecal incontinence [22, 95]. The relative humidity is showed to increase with use of foam, viscoelastic foam, gel and water cushions [22, 95]. Support surfaces with porous construction allow air exchange and help to lower the relative humidity [21, 95]. One example is the nonporous nature of the gel cushions.

Chapter 3

Blood flow measurements

With measurement of the tissue blood flow, the physiological effect on the tissue viability during externally applied loading can be studied. Blood flow measurements can and have been used to investigate the etiology behind pressure sores and to better evaluate antidecubitus mattresses.

Tissue blood flow can be measured non-invasively with laser Doppler flowmetry, laser Doppler imaging, and photoplethysmography (PPG). Other methods used for studying the tissue viability in the research of pressure sores are, for example, measuring of transcutaneous oxygen tension ($TcPO_2$), transcutaneous carbon dioxide tension ($TcPCO_2$), radioactive isotope clearance, and video microscopy (Paper I). $TcPO_2$ and $TcPCO_2$ reflect the superficial changes in tissue perfusion and the metabolic status [21, 60] but this method requires heating of the skin, that might change the tissue blood flow. Radioactive clearance gives the flow values in absolute units but involves needle insertion, radioactive exposure, and access to a gamma camera [49].

With ordinary laser Doppler flowmetry and PPG the blood flow is only measured in a single or a few points during externally applied pressure. However, significant spatial blood flow differences in tissue with apparent homogenous perfusion have been demonstrated [96, 102]. With a laser Doppler Imager the spatial variation in perfusion can be rendered, but this instrument requires free access to the tissue. So today, no non-invasive method is accessible for measuring spatial variation in tissue blood flow during external loading.

Optical properties of the tissue

Before the two optical methods for blood flow measurements, laser Doppler flowmetry and PPG, are described, an understanding of how light interact with the human tissue is needed.

Light that is incident on the tissue interacts with the tissue structures through reflection, absorption and scattering [4]. The interaction of skin and blood is wavelength dependent. In the wavelength range of 600 to 1300 nm, called ”the optical window of the tissue”, the absorption of light in the tissue is at a minimum. The optical properties and hence the absorption of light depends on the chromophores in the tissue, for example, melanin, bilirubin, water, oxyhemoglobin, and deoxyhemoglobin. At shorter wavelengths than 600 nm the absorption due to hemoglobin, increases and at longer wavelength than 1300 nm, the absorption due to the water content in the tissue increases.

In addition to absorption, the optical properties depend on the different scattering action due to the inhomogeneous structure of the tissue. The scattering in tissue is due to differences in the tissue's refractive index, corresponding to physical inhomogeneities such as structures and particles. The spatial distribution and intensity of the scattered light depends on the size and shapes of the structures/particles and the actual light wavelength, and the mismatch in refractive indices. In the wavelength range of 300 to 1000 nm and in non-pigmented skin, scattering dominates over absorption. The direction of the photon after scattering is characterized by the anisotropy factor.

The epidermis, dermis and subcutaneous tissue layers have different optical properties. The epidermis, 50 to 150 μm thick, contains melanin, which strongly absorbs visible light of shorter wavelengths and UV light [4]. In dermis, 1 to 4 mm thick, the chromophores in blood; oxyhaemoglobin, deoxyhaemoglobin, beta-carotene, and bilirubin are the major absorbers and the scattering is determined by the collagen fibers. In general, for the skin and for all wavelengths, scattering is much more important than absorption [100]. The anisotropy factor for the stratum corneum, epidermis, and dermis indicate that these tissue layers can be considered to be highly forward scattering. This makes it possible to measure blood flow in the deeper tissue layers.

Longer wavelengths of light, used by either laser Doppler flowmeter or PPG, generally penetrate deeper into the tissue [4]. The penetration depth of light in tissue is defined as the depth at which the intensity is reduced by 1/e (37 %).

Verification of the laser Doppler method has been performed with Monte Carlo simulations [51, 80]. With Monte Carlo simulations the light interaction with the human tissue is simulated based on random numbers and probability distribution functions. A large number of photons are simulated, one at the time, and the probability of all photons to undergo scattering and eventually absorption into the simulated tissue will determine the single photon's pathway. The large number of photons gives a reliable result. The probability distribution functions can be described by the optical properties of the simulated tissue, the absorption, and scattering coefficients, and the anisotropy factor.

Laser Doppler flowmetry

With laser Doppler flowmetry [49, 94] and laser Doppler imaging [102] the microcirculation in small tissue volumes is assessed. The measurement principle is based on that monochromatic laser light is sent via an optical fiber towards the tissue and is spectrally broadened due to scattering by moving blood cells, i.e. Doppler shifted, Figure 3.1. This frequency change is utilized for estimation of the tissue blood flow [14, 94]. A receiving fiber will collect and transport the backscattered light from the tissue to a photodetector. Both shifted and non-shifted photons reflected from the tissue will be detected. The perfusion value, the values of the blood flow, is defined as the average velocity of the erythrocytes times the concentration of erythrocytes in the illuminated tissue volume, in the case of low haematocrit level and low velocity [73]. The perfusion can be presented in Volt (V) or arbitrary units.

Laser Doppler flowmetry is confirmed to reflect the microcirculation at a tissue depth of typically a few hundred μm [51, 83]. The measuring depth of laser Doppler is except from wavelength and tissue characteristics dependent, also depending on the size, separation and placement of the optical fibers used.

The first lasers used were gas lasers and the most common is the HeNe laser, with a wavelength of 632.8 nm. Today, usually semiconductor lasers (780 nm) are used in laser Doppler flowmeters. This gives the advantages of, besides a deeper measurement depth, a reduced dependency on skin pigmentation due to the lower absorption of melanin at 780 nm [59]. The dependence on oxygen saturation is also reduced

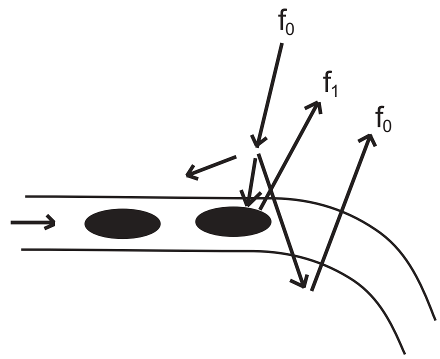

Figure 3.1: Genesis of Doppler shift in the frequency of the light when monochromatic light is scattered due to moving erythrocytes.

since the change in absorption between oxyhaemoglobin and deoxyhaemoglobin is smaller at 780 nm than for example at 632.8 nm.

Photoplethysmography

In the 1930's Hertzman and Spealman [47] and Matthes and Hauss [68] described that changes in the blood content could be assessed with variations in the light transmission through a finger or an ear lobe. By definition, a plethysmogram should record volume and volumetric changes in the blood vessels of an organ.

The principle of PPG is that light sent into the tissue is attenuated due to reflection, scattering and absorption of light and that variations in the attenuation occur due to the amount of blood in the tissue illuminated. Blood has a light absorption coefficient that is higher than that of the surrounding tissue, thus an increase in the amount of blood causes, a corresponding decrease in the intensity of light detected [4, 68].

The PPG signal can be divided into two parts a direct current signal, the DC signal, and an alternating current signal, the AC signal. The level of the DC signal is related to the attenuation in static structures in the tissue and is therefore correlated to the blood volume [47]. The AC signal's pulsative pattern is directly correlated to blood flow and is synchronous with the heart rate [23, 109].

The AC and the DC signal is also related to variations with origin in low-frequency processes, for example autoregulation, temperature regulation, blood pressure regulation and variations synchronous with the respiration [74, 57]. The variations in the AC signal might also depend on light scattering and reflection due to the erythrocytes orientation, axial accumulation and their deformation [38, 63].

There are two modalities of PPG; transmission mode and reflection mode. In transmission mode, the light source and photodetector are on each side of the extremity and in reflection mode the light source and photodetector are placed adjacent to each other on the skin.

The attenuation of light causing the variations in the PPG signal depends on the light frequency or wavelength [40], the amount of blood in the tissue underneath the probe, the haematocrit level, the actual oxygenation of the blood, and the light source/detector separation [4, 79].

As with laser Doppler, the penetration of light with PPG increases with increasing wavelength and with increasing distance between light source and photodetector [107, 108, 37]. The measurement volume is also related to the geometry of the optical probe [64]. For the assessment of superficial blood flow, green light is suggested to be used and for reflection of the muscle blood flow, infrared (IR) or near-infrared light is suitable [39, 45, 85, 107, 108].

The mechanism behind the generation of the AC signal is twofold; a) during systole, the blood volume in the tissue increases, more light is absorbed and the signal decreases, b) during systole the erythrocytes orientation etc. affects the signal in the way that it decreases. During diastole the process is vice versa for both a) and b). To mimic the pressure pulse and simplify interpretation of the two signals, the PPG signal is inverted, Figure 3.2. The second top in the pulse, called the incisura, is caused by the elastic recoil of the aorta and other large arteries and follows systole. The signal from PPG reflects the blood flow at a somewhat larger tissue depth compared to laser Doppler and also from a larger measurements volume [18, 83]. According to Anderson and Parrish, IR light (780 - 960 nm) penetrates the tissue to a depth of twice that of the HeNe laser (632.8 nm) [4].

PPG has been used for investigation of external occlusion pressure for blood vessels [72], blood flow response to external loading of the tissue [9, 10, 11], the

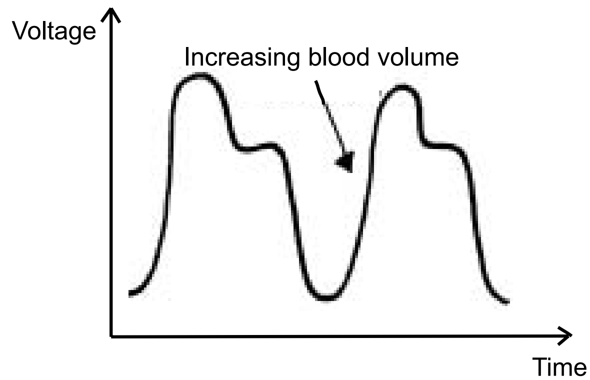

Figure 3.2: The inverted pulsative PPG signal.

healing potentials of pressure sores [61], determination of free flap ischaemia [39], and monitoring of skin and muscle perfusion and reactive hyperaemia [85, 107, 108]. Measuring of the oxygen saturation with pulse oxymetry is based on the same principle as PPG and utilizes two different wavelengths to determine the oxygen saturation in the tissue. PPG has also been suggested to be used for evaluation of different pressure relieving support surfaces [72].

Laser Doppler flowmetry and PPG are based on two different physical principles. Therefore it is not possible to exactly compare the blood flow parameters obtained from the two methods, respectively, but relative changes in blood flow can be used for analyzing signals from the two methods, and make comparisons possible.

Aims of the thesis

The aims of this thesis were to:

- perform a critical review of earlier published literature regarding the relevant factors for development of pressure sores and suggest parameters important to regard and measure when evaluating antidecubitus mattresses,
- investigate the importance of the parameters suggested for evaluation of antidecubitus mattresses, including the skin blood flow response to thermal stimuli and application of shear stress,
- develop a non-invasive optical sensor with the possibility to discriminate between different tissue depths and render the skin blood flow during external loading.

Chapter 4

Materials and methods

To achieve knowledge about the etiology and development of pressure sore and related work on evaluating antidecubitus mattresses, a comprehensive and critical review, Paper I, was performed. The purpose of the work was to identify the factors in pressure sore etiology and investigate which parameters are used in evaluation of antidecubitus mattresses today and suggest the important parameters to regard for improvement of the evaluations.

Over 120 journal papers and conference proceedings were critically read and analyzed to obtain knowledge about the contributing factors considered important in pressure sore etiology and the published work on performed tests with different support surfaces. The review was delimited to mostly concern measurements performed on mattresses and not wheelchair cushions.

To investigate the blood flow response to increased skin temperature in tissue areas prone to pressure sore development the study described in Paper II was performed. Differences in blood flow response to increased skin temperature, in areas prone and not prone to pressure sore development, might explain the tendency for pressure sore development. In addition, investigation of the thermal effect on blood flow should give an indication if it is of importance to evaluate antidecubitus mattresses in respect to their thermal properties.

The study in Paper II was performed with 13 healthy individuals in the age between 25 to 39 years. The heating of the skin was achieved with three in-house heating probes, diameter 2.5 cm, into which an optical fiber from a laser Doppler flowmeter (PeriFlux df2, Perimed, Järfälla) was inserted. Measurements of the blood flow response were conducted at the left shoulder, heel, and upper arm. The shoulder and heel were regarded as body locations more prone to pressure sore development than the upper arm. The measurement procedure started with an acclimatization time for the individuals before blood pressure and skin temperature at the three locations were measured. The temperature in the room was kept at a constant temperature.

The skin at the three locations was heated to 32° C, 35° C, and 38° C. Measurement of the blood flow was performed after 5 minutes of stabilization at each temperature. The mean perfusion value, in Volts, for all test subjects was analyzed with Student's t-test (paired samples).

In Paper III and Paper IV, the blood flow response in the tissue over sacrum, during external loading has been studied. It is common knowledge that external loading resulting in tissue ischaemia, is the primary factor in the development of pressure sores. In spite of that, not many researchers reflect over or neglect, the fact that the loading of the tissue at the tissue/support surface interface, is a combination of pressure and shear stress and that the amount of loading is not easily related to the pressure and shear stress inside the tissue.

To verify our conclusion from Paper I, i.e. that only measuring the interface pressure when evaluating antidecubitus mattresses is not enough, a study on the effects of blood flow due to shear stress was performed in Paper III. To study the shear stress effect on the blood flow, tangential loading of the tissue at the sacral area was applied. The blood flow response was recorded with a laser Doppler flowmeter with two channels using a light wavelength of 780 nm (Moor Instruments MoorLAB, UK).

By tangentially pulling the skin, shear stress and a minimum of pressure was applied to the tissue. The loading situation mimics the situation when the head end of the bed is elevated.

Twelve voluntary healthy test subjects were included in the study, six elderly subjects between 67 and 81 years and six younger subjects between 20 and 39 years. Since elderly have an increased risk of developing pressure sore, the difference in blood flow response between young and elderly healthy subjects was in focus. After acclimatization in prone position and before the measurement procedure started, pulse, blood pressure, and the skin temperature at the sacral area were measured.

The skin temperature was also measured after the measurements had been performed. The room temperature and the relative humidity were noted and kept constant.

Before the loading with the first weight, the baseline perfusion was recorded for 20 seconds. Thereafter the perfusion was continuously recorded during the loading with 250 g, 500 g, 1000 g, and 1500 g. Each load was applied for 20 seconds. After removal of the final load of 1500 g, the perfusion was recorded for an additional 20 seconds to assess possible reactive hyperaemia.

For comparison of the circulatory reactions between the different test subjects and for analyzing the result, the relative alternation i.e. the difference between baseline perfusion and the perfusion during each provocation, was calculated. The relative perfusion during each provocation was calculated as the mean perfusion value during the first 20 seconds of loading with each weight. The results were analyzed with two-way analysis of variance, Student's T-test (paired samples), and Person's correlation.

The results from Paper I-III together with the question about at which tissue layer pressure sores start to develop, made it attractive to measure the blood flow at different tissue depths. This led to the development of an optical sensor for non-invasive measurement of the blood flow in tissue exposed to external pressure, Paper IV. The intention was that the novel optical sensor should be used both in etiology studies and in the future for evaluation of antidecubitus mattresses. The optical probe should render both the superficial and deeper tissue blood flow. The methods, laser Doppler flowmetry and PPG, were chosen since they are non-invasive and established methods, that do not affect the circulation and together can render the tissue blood flow at several tissue depths. With use of several light wavelengths and suitable probe geometry, the blood flow in the capillaries, the superficial skin, and the muscle can be assessed, Figure 4.1.

For the first measurement with this new sensor, the optical probe was designed to be inserted into a bunk on which the test subjects were placed, Figure 4.2. A laser Doppler flowmeter with a wavelength of 632.8 nm (PeriFlux df2, Perimed, Järfälla) and an in-house developed PPG instrument with three channels (Department of Biomedical Engineering, Linköping University) were used. For rendering the superficial skin blood flow the laser Doppler flowmeter and PPG with green light (560 nm) were used and for rendering the deeper skin and the muscle blood flow, PPG

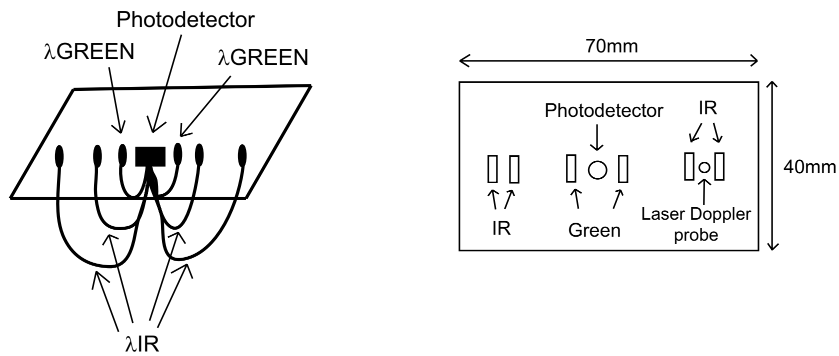

Figure 4.1: The principle of PPG and our design of the optical probe.

with IR light (810 nm) was used. Three pairs of light emitting diodes, LEDs, were used as light sources in the PPG and placed symmetrically around a photodetector. The pair of green LEDs was placed at a distance of 5 mm from the photodetecor and the two pairs of IR LEDs were placed at distances of 10 mm and 25 mm. With this combination of wavelengths and distances measurement depths of approximately 2 mm, 8 mm and 20 mm, respectively, were assumed.

During testing of the sensor, the laser Doppler flowmeter experienced problem with calculation of the perfusion signal, since IR light from the LEDs in the PPG was disturbing the detector in the laser Doppler flowmeter. The contribution of IR light resulted in a false high calculation of the perfusion. This problem was solved through switching the IR LEDs on and off in sequences of 30 seconds. This resulted in sequential measurements with the LDF and the IR PPG, respectively. The signal from the green PPG could be recorded continuously.

To be able to relate the blood flow response to the magnitude of the applied pressure, a thin and flexible pressure sensor (Flexscan OEM 400N, CA Mätsystem, Täby, Sweden) was placed on the optical probe. The signals from the pressure sensor, the laser Doppler, and the AC and DC signals from the three PPG channels were A/D converted and recorded with a DAQ-card (6062E, National Instruments, Sweden) at a sampling frequency of 60 Hz using a Labview program (Labview 6.1,

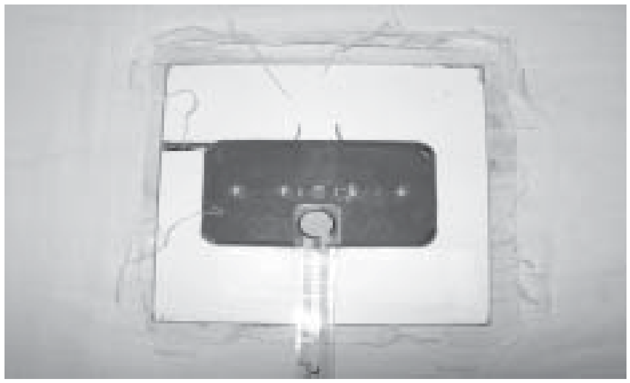

Figure 4.2: The optical probe inserted in the bunk.

National Instruments, Sweden).

Preliminary measurements with the optical probe during external loading of the tissue have been performed on four voluntary healthy females. The test subjects rested in prone position on a hard bunk for 15 minutes before blood pressure, pulse, body temperature, and skin temperature at the sacral area were measured. To assess the blood flow response to tissue compression, the test subject was placed in supine position and the tissue over sacrum was compressed with weights of 4 kg and 7 kg, Figure 4.3. The loads applied were cylindrical and placed on a square-shaped, rigid wooden plate in which the LEDs embedded in silicone was inserted. Before the beginning of loading, the baseline skin blood flow was measured for 5 minutes. Thereafter 5 minutes of loading with 4 kg, 10 minutes of unloading, and 5 minutes of loading with 7 kg weight followed. After the removal of the 7 kg, the blood flow was recorded for 5 minutes to assess possible reactive hyperaemia. Every new sequence of loading or unloading was started with the IR LEDs switch on. The total time for the measurement procedure was about one hour. The forces applied to the tissue included both external pressure and shear stress since the weight could not be placed parallel to the bunk due to the shape of the sacral area.

Figure 4.3: Loading of the tissue.

Chapter 5

Results

In this chapter the results from Paper I-IV will be presented.

Paper I

The result from Paper I showed that the factors in pressure sore development are numerous, and can be divided in intrinsic and extrinsic factors, also referred to as indirect and direct factors. The loading of the tissue and the structure of the tissue are both inhomogeneous, resulting in pressure gradients and shear stress in the tissue. From the review it became clear that no simple relationship between applied external loading and tissue blood flow exists. These facts together with the individuals' different tissue response due to the physiological condition, makes it insufficient to only measure the interface pressure when evaluating antidecubitus mattresses.

Although in many of the evaluations performed, only interface pressure have been measured. In some of the studies it has been reflected over that only interface pressure measurement as a indication of the mattress's effect on the tissue, is not sufficient. Some suggestions of methods for measuring shear stress have been presented.

In some of the reviewed papers, methods for measurement of the tissues viability during external loading have been presented, for example, laser Doppler flowmetry, laser Doppler imaging, PPG, transcutaneous oxygen tension, transcutaneous carbon dioxide tension, video microscopy, and radioactive isotope clearance. After all, tissue ischaemia is the cause of pressure sores and assessing the blood flow must be a better way to evaluate antidecubitus mattresses. The non-invasive optical methods, laser Doppler flowmetry and PPG, are suggested suitable methods for measuring of blood flow due to their minimal effect on the tissue and the tissue blood flow.

As a complement to the blood flow measurements, interface pressure measurement should be performed with a pressure sensitive mat for rendering the spatial variations. Large spatial variations in blood flow can also be seen in adjacent tissue areas therefore blood flow measurements also ought to performed in larger areas.

The conclusion in Paper I is that evaluation of antidecubitus mattresses has to be made in respect to several parameters due to multiple extrinsic factors in the development of pressure sores. At least the three parameters; interface pressure, the thermal properties of the mattress and the blood flow in the tissue during loading from the mattress should be regarded and assessed.

The result from Paper I initiated Paper II-IV, involving studies of the effect on tissue blood flow due to increased skin temperature and application of pressure and shear stress at areas prone to pressure sore development.

Paper II

In this paper, the skin temperature effect on the skin blood flow in areas prone to pressure sore development was assessed in 13 healthy individuals. The results showed that healthy individuals increase their blood flow in the upper arm and shoulder with increased skin temperature, Figure 5.1.

The normal skin temperature measured in the test subjects was close to 32° C. When the skin temperature was increased from normal skin temperature to 38° C, the perfusion in the upper arm increased in average 27 times and in the shoulder 17 times. A significant increase in blood flow occurred between skin temperature of 35° C and 38° C, for both, the upper arm ($p<0.01$) and shoulder ($p<0.01$). The shoulder had a statically significantly higher perfusion compared to the upper arm at normal skin temperature ($p<0.05$), 32° C ($p<0.025$) and 35° C ($p<0.025$). At a skin temperature of 38° C, there was no significant difference between the perfusion at the shoulder and the upper arm.

For many of the healthy test subjects included in this study, large fluctuations

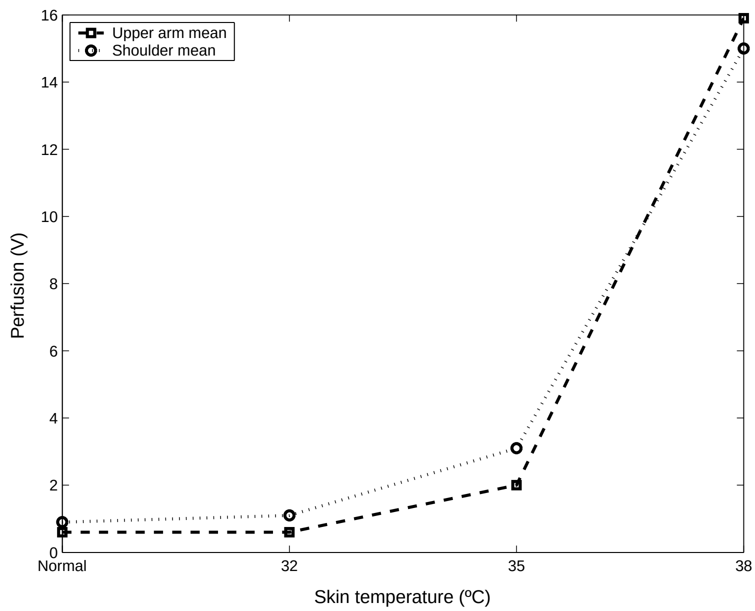

Figure 5.1: Relation between skin temperature and the mean perfusion in the upper arm and shoulder.

in the heel perfusion, could be seen at all temperatures. For this reason, the mean perfusion value of the heel was not presented in Paper II. In many of the test subjects, the heel had a lower blood flow at 38° C compared to blood flow at the upper arm and shoulder.

The result from Paper II indicates that increased skin temperature greatly affect the skin blood flow in healthy individuals and that different areas might have different possibility to response to increased skin temperature. This makes it important to evaluate antidecubitus mattresses in their ability to maintain a favourable climate close to the skin.

Paper III

The results from Paper III clearly indicate that shear stress applied at the sacral area, negatively affect the superficial blood flow, Table 5.1.

	250 g	500 g	1000 g	1500 g	Unloading
Elderly sensor 1	-12 %	-11 %	-20 %	-35 %	16 %
Elderly sensor 2	-30 %	-34 %	-43 %	-70 %	-6 %
Younger sensor 1	-3 %	-3 %	-12 %	-46 %	23 %
Younger sensor 2	6 %	2 %	-12 %	-49 %	22 %

Table 5.1: Mean relative change in perfusion in the elderly and the young group, for each level of loading and unloading.

A significant reduced skin blood flow could be seen with the largest load of 1500 g in the most inferior placed probe at the sacral area ($p<0.01$). With the lower levels of loading, an increased blood flow was recorded in some of the individuals. When the 7 kg weight was removed from the tissue, an increase in blood flow, a reactive hyperaemia, in the tissue followed. The reactive hyperaemia was significant in the sensor placed most superior. No significant difference was seen in blood flow response between the elderly and younger group or in perfusion between the two laser Doppler probes.

From the result it was found that the skin temperature had increased significantly during the loading ($p<0.01$) and that the increase was significantly higher in the younger group ($p<0.01$). However, no correlation was found between temperature changes and changes in skin blood flow from before the measurements and with unloading of the tissue (probe 1 r = 0.211, probe 2 r = 0.399), indicating increased skin temperature due to reactive hyperaemia in the skin.

Paper IV

From the first preliminary measurements performed with the optical sensor that combines laser Doppler flowmeter and PPG, it seems like the two methods, complement each other when studying the blood flow response to external loading at different tissue depths.

However, with the present design of the probe and used instrumentation, interference problems occurred. As mentioned in Chapter 4, Materials and Methods, IR light disturbed the laser Doppler flowmeter, which required sequential measurements with the two methods. Furthermore, a new interference problem was observed during the measurements. The photodetector in the PPG instrument recorded a signal from the two IR channels, also when the IR LEDs were switched off. The light detected consisted of an additional pulsative PPG signal due to the laser light's interaction with the vascular bed in the tissue volume. This pulsative contribution from the laser could be observed separately when the IR LEDs were switched off, but was added to all three PPG channels and present all the time, Figure 5.2. This makes it unclear from which tissue depth the PPG signals originate since the signal is a mixture of light with different penetrating wavelengths.

A preliminary analysis of the result from the measurements, in spite of the interference problems, has been performed. The top-to-top value of the pulsative PPG signals was interpreted as blood flow and changes could easily be observed. The weights were applied to the tissue for 5 minutes each, and started 5 minutes (4 kg) and 20 minutes (7 kg) into the measurement recording. Large individual differences in blood flow response between the four test subjects were seen. Decreases in both the superficial and deeper blood flow at the sacral area were observed with as low levels of loading as 30 mmHg, corresponding to the loading with the 4 kg weight, Figure 5.3. In all individuals, a compensation to the external loading could be seen as an increase in blood flow, Figure 5.4. The compensation could be seen in the superficial and the deeper blood flow.

A summery of the four individuals blood flow response to the external loading

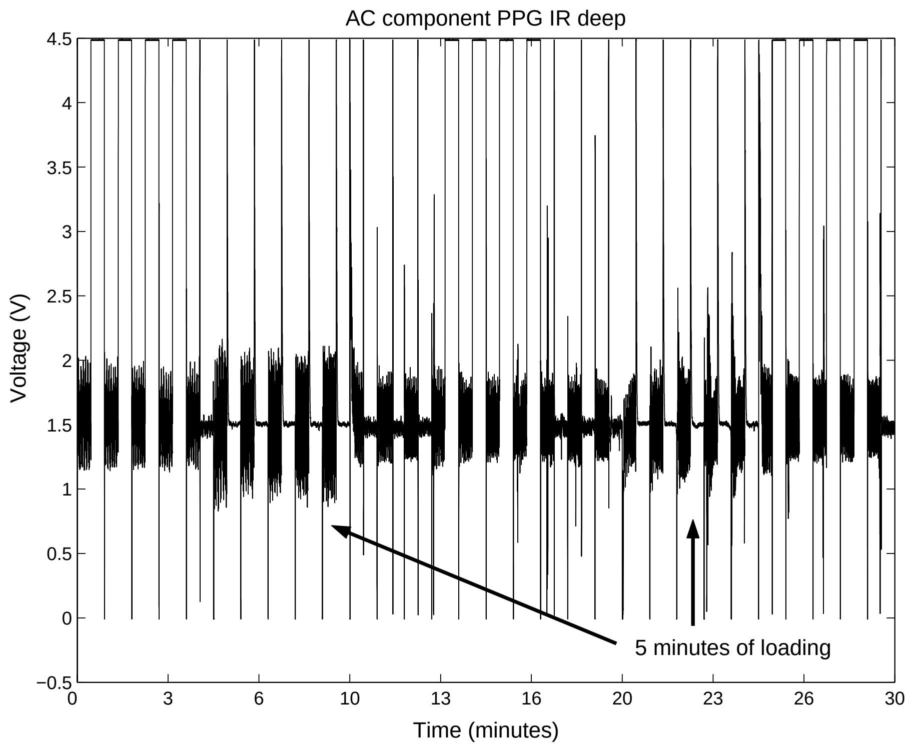

Figure 5.2: The figure shows the pulsative contribution from the laser Doppler during that the IR LEDs are switch off.

	Person 1	Person 2	Person 3	Person 4
PPG Green	Decrease	Decrease	Increase	Decrease
PPG IR	Increase	Increase	Increase	Increase
PPG IR deeper	Decrease	Increase	Increase	Decrease
Laser Doppler flowmeter	Increase	Decrease	Increase	-

Table 5.2: Blood flow response at the different measurement depths

can be seen in Table 5.2. The same response, decrease or increases, occurred during loading of both the weights. The results from the blood flow measurements with the two methods, indicate that much information can be obtained when studying the blood flow response at different tissue depths.

The recorded laser Doppler perfusion signal in one of the individuals could not be analyzed due to poor contact between the optical fiber and the skin. The signals from the other three individuals were analyzed. Two of the individuals increased their superficial blood flow during loading, Figure 5.5. In the third individual, who's blood flow decreased during loading, a clear reactive hyperaemia could be seen with removal of the load.

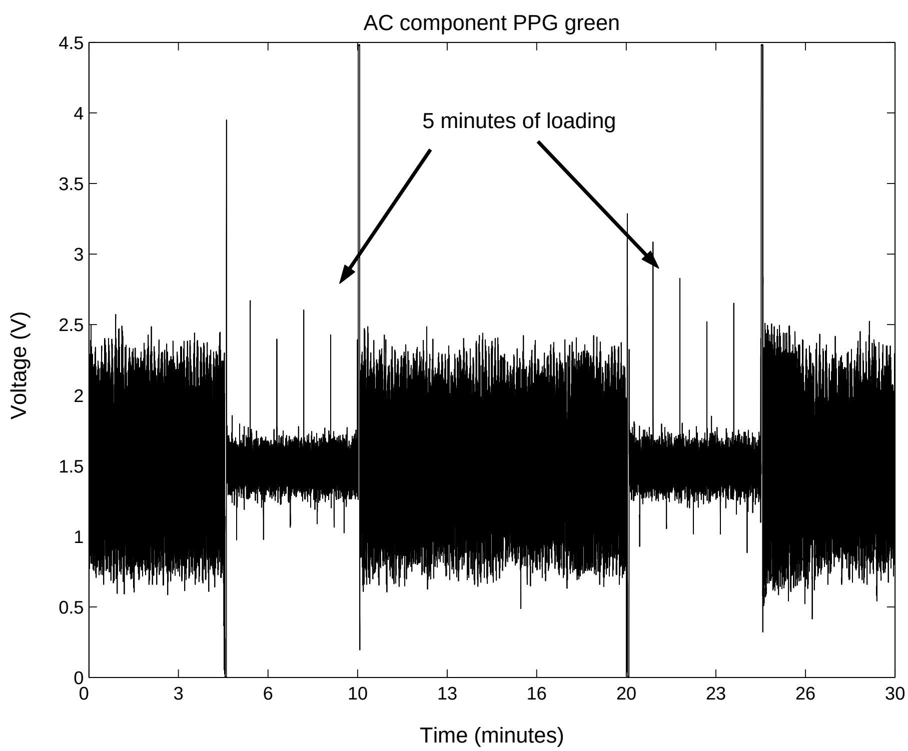

Figure 5.3: The pulsative green PPG signal recorded in one of the individuals shows a decrease in blood flow during external loading with 4 kg and 7 kg, respectively.

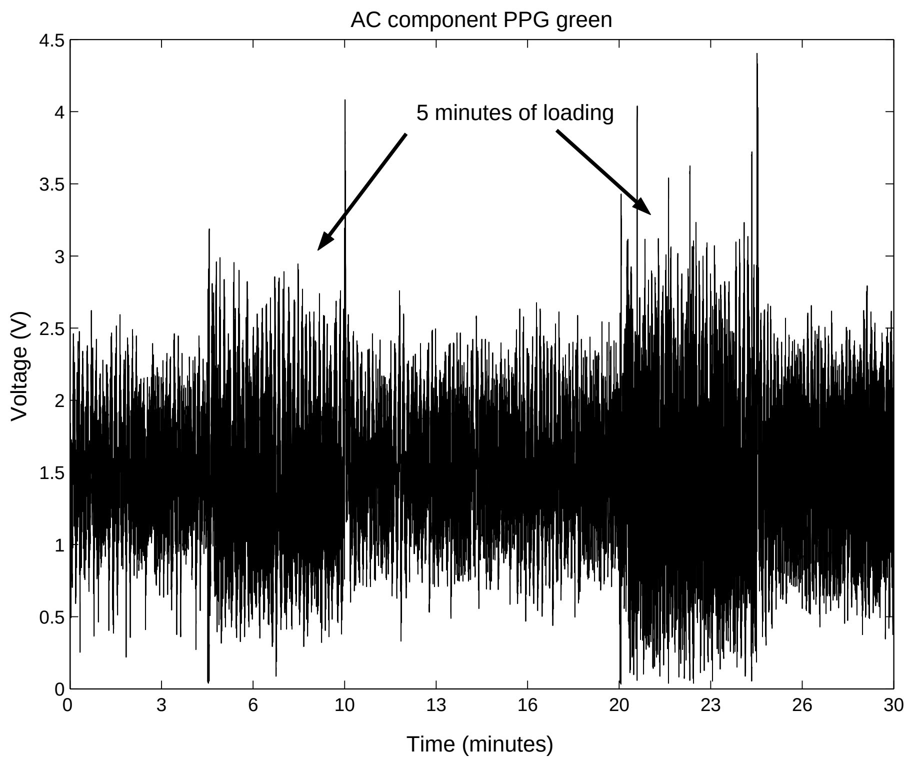

Figure 5.4: Increase in blood flow during external loading with 4 kg and 7 kg, respectively, recorded by the pulstive green PPG signal in one of the individuals.

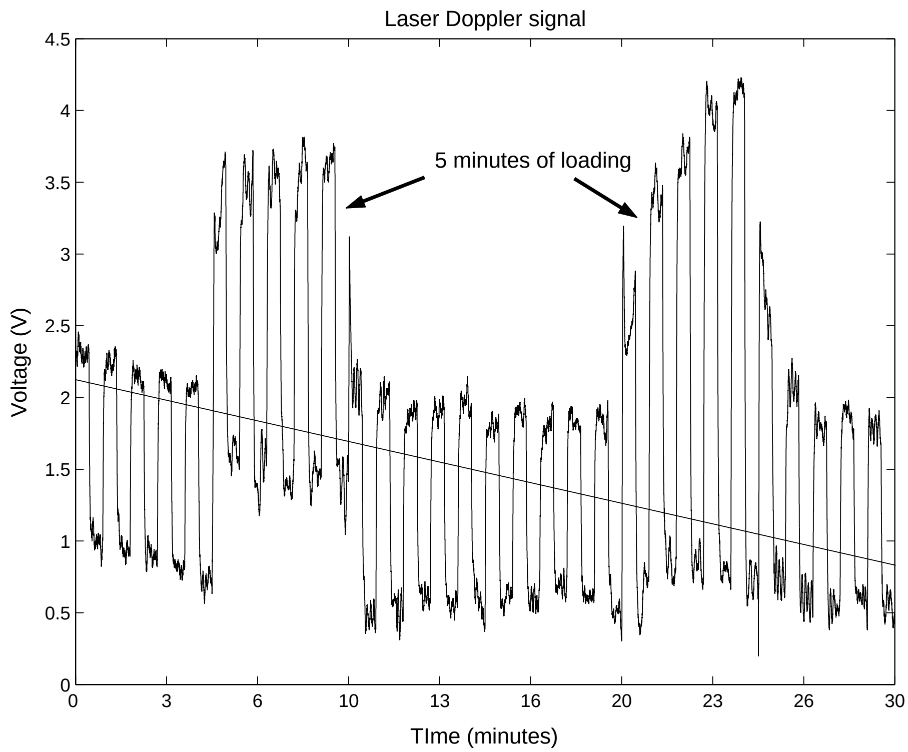

Figure 5.5: The figure shows the laser Doppler signal from one of the individuals in which the superficial blood flow increased during loading of the tissue. The signal under the line is to be studied since it is recorded with the IR LEDs switched off.

Chapter 6

Discussion

Evaluation of antidecubitus mattresses is important for personal in the health care sector to make well-founded decisions when choosing mattresses for prevention or in treatment of pressure sores. More important is that the mattresses available on the market, should be evaluated and proved to have a positive influence on the individual's tissue viability. The result from this thesis suggest that the parameters interface pressure, thermal properties of the mattress and it's affect on tissue blood flow ought to be regarded and assessed in evaluations. The studies performed on the influence on the tissue from thermal stimuli and application of pressure and shear stress, emphasize the relevance and importance of measuring blood flow.

When lying in bed the temperature and also the relative humidity increases, normally this should lead to an increased blood flow. This is in accordance with the result from Paper II showing an increased skin blood flow due to increased skin temperature in healthy individuals. Tissue that suffers from an impaired blood flow due to external loading and is exposed to an increase in temperature, will experience an even larger blood flow deficit. In addition, elderly are suggested to have an impaired ability to react with increased skin blood flow to thermal stimuli [29] and the sacral area is suggested to have a lower baseline blood flow [48] and a poorer blood flow response to external loading [87]. The result presented in Paper I regarding thermal properties of support surfaces and the result from Paper II emphasize the importance of evaluating the support surfaces' and their covers' ability to maintain an acceptable microclimate.

Many studies have presented results with great individual differences and age related differences, in blood flow response to external loading and with unloading of the tissue. In Paper III and IV, increases in blood flow were recorded in some of the individuals during loading of the tissue. This is due to vasodilatation of the vessels for compensation of the impairment in blood flow during external tissue loading, and has been reported by other research groups [5, 35, 84, 105]. The result from Paper III showed no significant difference in blood flow response between the elderly and younger individuals, this could be due to the elderly individuals' good health and high activity in everyday life.

External loading of the tissue involves shear stress and the result from Paper III shows that the superficial tissue blood flow is negatively affected by shear stress. This result implies the importance in regarding shear stress as a factor in the development of pressure sores and strengthens our opinion that measuring blood flow would be a more direct and better parameter than solely measuring interface pressure, when evaluating antidecubitus mattresses.

Shear stress occur inside the tissue and is difficult to measure. Nevertheless, the development of shear stress sensors is a hot research topic today. The sensors presented in literature indirectly reflect the true shear stress in the tissue by measuring the shear force at the interface between the support surface and the body.

Two theories about the development of pressure sores exist. One called top-to-bottom and the other bottom-to-top, referring to where the sores start to develop. Perhaps pressure sores can be developed in both ways depending on the circumstance. We believe that the on-going development of the optical sensor will lead us closer to understanding the development of pressure sores, since the blood flow at several depths can be assessed. This knowledge is also important when deciding at which measurement depth/depths to measure the blood flow when evaluating mattresses.

The two optical methods, laser Doppler flowmetry and PPG using green and IR light, are attractive to combine for studying larger tissue volumes and the blood flow at several different vascular depths. It can be assumed that PPG using green light measures more superficially than IR PPG and deeper than a laser Doppler flowmeter using a wavelength of 632.8 nm. We have chosen to include measurements with the laser Doppler flowmeter in the optical sensor since it renders the most superficial skin blood flow and since the method has been commonly used in the research field of pressure sore etiology and evaluation of antidecubitus mattresses.

Large spatial variation in pressure and in blood flow can be seen in adjacent tissue area. It is therefore preferable to use measurement methods, for both the interface pressure and blood flow, that render the spatial heterogeneity when evaluating antidecubitus mattresses. With the use of PPG in the optical sensor, a larger tissue volume is illuminated and reflected since the LEDs are placed on both sides of the photodetector. However, the sensor has only one measurement point with the laser Doppler flowmeter. In Paper IV, the sacral area used for measurements is very delimited, and therefore a relative large part of it can be rendered with our sensor.

Preliminary measurements have been performed with the new optical sensor. However, interference problem occurred and a light contribution from the laser Doppler flowmeter was added to all three PPG channels. The contribution from the laser was relatively small compared to the detected light from the LEDs in the PPG. With the implementation of optical filters and rearranging the location of the laser Doppler fiber, we believe that simultaneous measurements without interference can be performed.

The result from the preliminary measurements performed shows large differences in blood flow response to the external loading between the four individuals. Differences in blood flow response to the external loading can also be seen in the different channels rendering the blood flow at different tissue depths. Decreases as well as increases in blood flow during application of the 4 kg and 7 kg weights were recorded. The difference seen in blood flow response is very interesting and the optical sensor is believed to be very useful in studies of the pressure sore etiology and also for use in evaluation of antidecubitus mattresses.

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