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Overview

Infrared thermography and image analysis for biomedical use

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Abstract

Infrared thermography is used for measuring and analyzing physiological functions and pathology related to the body's thermal homeostasis and temperature. This review provides an overview of the technological advantages of infrared imaging, with the focus on new advances in and opportunities for infrared imaging, as a reliable medical diagnostic tool.

The review has four main parts. Firstly, a short history of thermography development in medicine is given. Secondly, an overview on the clinical and biomedical research results and methodological improvements in established applications of infrared thermography is provided. Thirdly, the details of published research and development results and activities of the last 3 years for time and frequency domain analysis of infrared video thermography recordings to study some vital functions of human physiology are discussed. Analysis of infrared video thermography streams resulted in important information on microvascular (arteriolar) function of the skin and of vital organs when exposed during an operation. This new set of parameters of microvascular function enhances the assessment of the cardiovascular system in chronic diseases e.g. in hypertension and diabetes. Infrared thermography provides valuable information when an organ's suitability for transplantation must be assessed based on quantifiable parameters of organ function and viability. Fourthly, a brief overview on a separate, exciting area of infrared imaging is provided as well: the development of a touchless polygraph system. It enables the study of the psychophysiological parameters of stress, by the assessment of breathing and pulse wave patterns by non-contact methodology, for lie detection purposes.

In conclusion, infrared imaging is a non-invasive, non-radiative, low cost detection tool, and its application area is constantly growing, along with technical improvements and advances.

INTRODUCTION

Medical diagnosis is based on both structural and on functional data, as well as patient history and subjective symptoms. Structural imaging methods are e.g. X-ray, ultrasound imaging, MRI, and the classical and electron microscopy also fall into the imaging category. Functional investigative methods – just to name a few – are ECG, blood pressure measurement, EEG, pulmonary air flow tests, thermography, etc. Medical diagnostic infrared imaging is a functional, passive and non-invasive method for analyzing physiological functions related to body thermal homeostasis or organ temperature and therefore its re-

sults cannot be directly compared to the results obtained by structural imaging methods. It is used to detect and locate temperature distribution characterized by a non-physiological increase or decrease in temperature at the body surface. Today's improved hardware detection systems with additional advanced software solutions make it possible to incorporate anatomical and physiological information by image fusion, which helps to generate information of affected areas.

Energy taken into the human body has different ways of distribution (chemical, mechanical, electrical, thermal, etc.). The organism's heat loss depends on ambient factors and is the result of conduction, convection, IR radiation, and of evaporation from the surface of the skin, while heat is lost via breathing as well. According to Planck's law the dry human skin, which has an emissivity of 0,98, is nearly an ideal black body and can be considered as a long wave IR radiator with a maximum wavelength emission at about 9.3 μm *(1)*. Human body has (at least after a cold stimulus) the highest temperatures in the head and neck regions, followed by the trunk, with decreasing temperatures over the limbs toward the acral regions. Bilateral symmetry is one of the most important characteristics of the human body's surface heat pattern *(2, 3)*. Any significant asymmetry of more than 0.7 °C can be defined as abnormal and may indicate a physiological or anatomical variance. Infrared thermography's use is based on experiences, namely some type of tumours and other pathologic conditions, especially inflammation, lead to hyperthermia (areas with higher amount of infrared emission), while degeneration, reduced muscle activity, poor perfusion, and certain types of tumors may cause hypothermia *(4)*. The technique involves the detection of infrared radiation intensity that can be directly correlated with the temperature distribution of a defined body region *(5)*.

Background

Hippocrates was the first physician in the scientific literature looking at body heat by putting mud on the abdomen observing its change in colour when getting dry. Santorio, an Italian physician, first used a »thermometer« based on Galilei's »thermoscope« while centuries later Wunderlich introduced thermal measurement into clinical routine *(6)*. Czerny documented the first infrared image of a human subject in Frankfurt in 1928 *(7)*. The medical use of infrared thermography started in 1952 in Germany, when physician Schwamm together with the physicist Reeh developed a single detector infrared bolometer for sequential thermal measurement of defined regions of the human body surface for diagnostic purposes *(8)*. Schwamm and Reeh also established the first medical association of thermography in 1954, which is today still active as the German Society for Thermography and Regulation Medicine (Deutsche Gesellschaft für Thermographie und Regulationsmedizin).

In clinical medicine thermography was initially used to search for breast cancer. L.R. Lawson in 1956 used thermometer for measuring temperature difference on

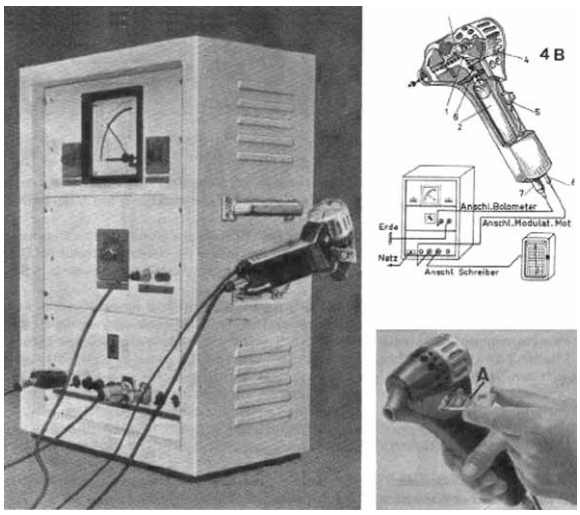

Figure 1. *First medical thermographic device developed by Schwamm and Reeh in 1952. (8).*

breast's skin surface covering the malignant tissue *(9)*. In 1963 Lawson and Chugtay studied the thermal emission of human body which led to the construction of the remote thermograph. The equipment was quite robust and needed a spacious room. In 1964 Fergusson announced the application of contact thermography. Plates used for this purpose had liquid cholesterole esther crystals. The first reliable clinical trials about the value of infrared thermography for breast cancer detection were published in 1969 and in 1974 (Gautherie), in 1969 and 1972 (Tricoire) and in 1972 (Davison) *(10, 11)*.

Methodological overview

Types of thermography according to history and sequence of appearing in medical literature are: contact thermography, remote sensing thermography and computer assisted thermography *(1, 12, 13)*. Contact thermography uses a sheet with liquid crystals (cholesterol esters) which must be in full contact with the skin and a camera which detects and records colour change. The black cholesterol crystals turns into different colours when exposed to thermal energy, and the actual colour is depending upon the energy absorbed by the sheet which are defined by the manufacturer for specified temperature ranges, while the room must have an ambient predefined temperature, in which the thermographic diagnostic procedure is performed. This allows abnormal vascular patterns and areas of increased temperature to be detected *(1, 13)*. Another type of contact thermography was made for quick diagnosis consisting of thin flexible foil to which liquid crystal carriers are being fixed. Remote sensing thermography is recording infrared emission from a 1–1,5 meter distance by an IR optical and detector system. The detected thermal image is produced by converting infrared energy into electrical signals and it is displayed on a proprietary monitor. First static thermography used robust cameras which processed pictures slowly and patients had to be in a still position for a relatively

long time. Today's dynamic remote sensing thermography utilizes methods, which captures and processes images very fast, usually in real-time. Computer assisted thermography uses high resolution thermal imagers and complex image transformations for image processing in order to extract some relevant features from thermal images.

In order to obtain a reliable, adequate result with thermography, patient preparation must be carried out and a carefully controlled environment should be provided (temperature, humidity, ventilation) *(14)*. Patient should avoid excessive sun exposure for at least 2 days before the examination. Food, liquids and medications intake are stopped before at least 2 hours of the planned examination *(1, 13)*. If needed, patient's skin can be cooled down, that should be done by exposing it to a small amount of 96% alcohol and then fanning. Patient must be seated and calm. Nowadays an area read-out of at least 8x8 pixels (image segmentation) should be used instead of single spot measurements *(15)*.

The past few years have witnessed significant developments in far infrared image capture and analysis technologies and methods. Since 2009 advanced amorphous Silicium-based uncooled infrared microbolometer sensors with 1.024 × 768 pixel resolution, active in the 8–14 μm spectral band, have become commercially available. This new generation of uncooled sensors provide much improved signal to noise ratio and spatial resolution, and thermal resolution of <0,01 K, for the analysis of still infrared images. Visual assessment is the current mainstream, routinely used methodology for the analysis of two-dimensional still infrared images. Many image analyzing algorithms have been developed to extract reproducible, objective, numerical features from the spatial characteristics of the infrared image, that provide for meaningful diagnostic or prognostic value. These newest results are representing the innovative features of multidimensional and multispectral IR imaging systems for medical diagnostic purposes developed in the Ruđer Bošković Institute in Zagreb, Croatia.

Thermography is a diagnostic method useful as a complementary method to other medical tests. Thermography, as any other diagnostic method, has its advantages and drawbacks. Advantages of thermography are as follows: it is a non-invasive, non-contact method, and doesn't utilize any harmful radiation. Detailed colour-coded images can be easily understood by patients due to their clear anatomical topology. High resolution thermography with advanced computer support deals with huge data sets and provides a new source of knowledge for reliable diagnosis. The drawback of thermography is its high vulnerability to exogenic disturbances (external heat sources, evaporative heat loss, etc.), that may introduce biases and/or may impair image quality by worsening the signal to noise ratio.

The European Medical Device Directive ensures that only properly validated, certified infrared camera systems are allowed to be used for medical purposes after the CE mark has been obtained. In 2007 the first medical infrared imaging systems (MammoVision, ReguVision and FlexiVision by InfraMedic) have received a CE certification allowing to be used as thermal measuring medical devices (Category 1) and matching the European Medical Directive legislation. In 2011 HEXIUM Technical Development Company, in cooperation with MEDIRLAB Biomedical Development Company have developed the MEDIRLAB Infradiagnostic® System, and received proper CE certification. There may be some other infrared devices without medical CE certification used for medical purposes, without properly certified measuring function *(16)*. Two accredited and co-operating medical societies covering infrared thermography, the German Society of Thermography and Regulation Medicine (DGTR) and the European Association of Thermology (EAT), together with the United Kingdom's Thermography Association, the Northern Norwegian Centre for Medical Thermography and the American Academy of Thermology promote the proper application of thermal imaging. The overall aim of these groups is the continuous improvement of medical infrared thermography and the development of appropriate protocols for clinical applications.

The technical capabilities of infrared imaging are constantly improving, due to – inter alia – computerized systems, using complex statistical data analysis, which provides highly reliable temperature readings *(17)* and increased thermal sensitivity *(18)*. Infrared thermography's envisaged use is a multidisciplinary assessment tool by experts from different medical specialties, utilized among standardized conditions *(19, 20, 21)*. The thermal imaging group from the University of Glamorgan has published a battery of tests for checking reliability of infrared cameras *(22, 23)* and is doing research to determine »normal« thermograms and to provide for standardized reference images. If methodological guidelines are carefully implemented, then IR thermography can achieve a high sensitivity and specificity in the diagnosis of certain medical conditions, and therefore, is a very useful diagnostic modality. If serial, consecutive imaging sessions are performed, then the trend (improvement or deterioration) of a disease or condition can be followed up, and a treatment's efficacy can be measured objectively, based upon numerical data.

Clinical applications

Infrared thermography has been established as a valuable diagnostic tool of clinical medicine, particularly in the assessment of the body shell. The biophysical and biochemical basis of cellular energy utilization and the molecular origin of standard metabolic rate have been well studied in mammals. Therefore infrared thermographic image interpretation has a clear scientific basis *(24)*. Circulatory and/or inflammatory disorders and conditions have significant impact on the thermal homeostasis of certain body regions, that is readily available for assessment by infrared thermography *(25–38)*.

Rheumatoid arthritis

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 *(39–41)*. 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

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 *(42–45)*. 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, that provides valuable information for further diagnostic procedures and individualised management of the disease and also has prognostic value *(42)*.

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% (*46*). 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) *(47)*. 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

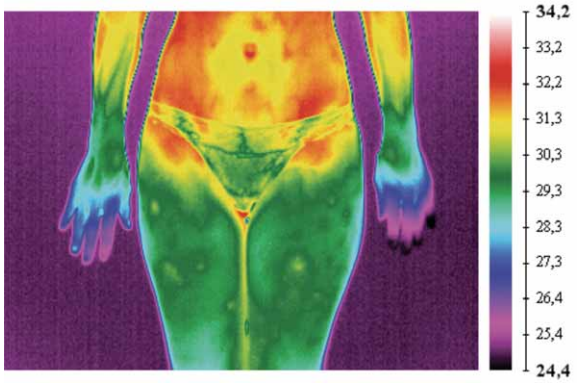

Figure 2. *Raynaud's disease of the fingers with excessively cold fingertip temperatures of the left hand.*

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 *(48)*. Quantitative assessment of pain-related thermal dysfunction by infrared thermal imaging is utilized in other body parts as well *(49)*.

Plastic and reconstructive surgery

In plastic and reconstructive surgery infrared thermograpy 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, valu-

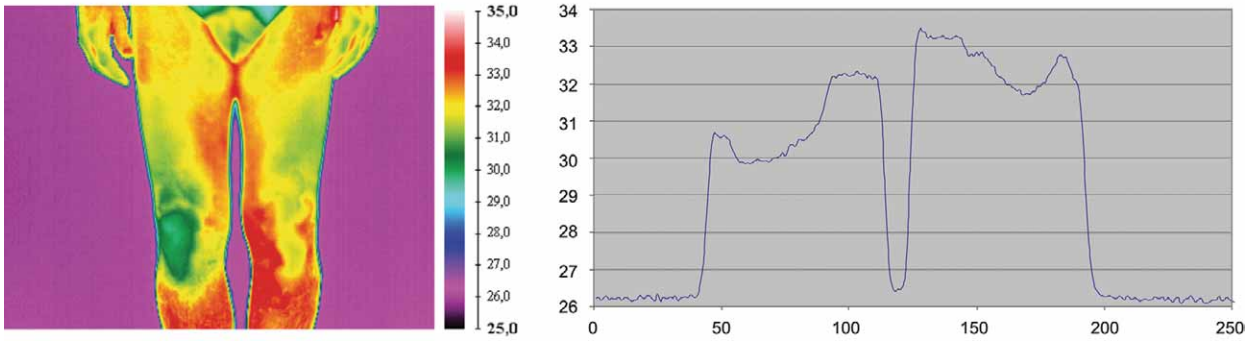

Figure 3. *Osteoarthritis of the left knee (left), temperature profile of the knees (right)*

able 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) *(50)*.

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 analysed by principal component analysis (PCA) in patients who were operated on for their cerebral pathologies (ischemic stroke, brain tumour, etc.). It has been shown, that the method is able to differentiate between cortical regions with good or poor perfusion *(51)*.

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 *(52–59)*. 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. By applying fast Fourier transform (FFT) on the thermal profiles over time, a PSD can be calculated. The calculated PSD reveals the dominant frequency bands of temperature fluctuations and their corresponding spectral power magnitude. This may provide a powerful tool for the investigation of a host of different pathophysiological phenomena characterized by changes in arteriolar function. Due to its vastly higher testing volume (1.000× – 10.000× that of LDF or LSI), infrared imaging represents a robust technology for the objective, quantifiable, numerical assessment of microvascular (arteriolar) function.

Regulation of arteriolar microcirculation is an adaptive mechanism of the body by which it accommodates the perpetually changing needs of its organs. Investigation of the microcirculation and the development of non-invasive methods for its predictive assessment is an active research field. Its importance lies in the fact that in cardiovascular and metabolic diseases, like hypertension and diabetes mellitus type 2, abnormal signs of microcirculation precedes full-blown organ damage. The potential role of microcirculatory abnormalities as an early prognostic tool for cardiovascular health assessment was known for a long time, but its proper functional investigation based on objective, reproducible parameters has been started over the past decade, by the availability of LDF-based technology. It is known, that the periodic pulsatile (oscillatory) function of the microcirculation in time causes minute temperature changes on the surface (usually skin) of the body. Furthermore, among experimental conditions, identical oscillatory signals can be detected on the surface of internal organs if they are surgically exposed to an infrared camera during operation. The minute temperature changes caused by the perpetual oscillations of the microcirculation present themselves as slightly oscillating heat-emission intensity on the body surface, mainly in the 8–14 μm region, and can be detected by infrared thermography *(54–58)*. The digitized signals can be analysed mathematically by FFT, and the PSD of the periodic (oscillatory) frequencies can be deconvoluted, which are characteristic for the function of the microcirculation.

The derangement in arteriolar function in systemic diseases affecting the microcirculation (diabetes, hypertension, obesity, metabolic syndrome) bear very similar patterns in different regions of the body and in different organs, and the skin's microcirculation represents very well the microcirculation of internal organs. Therefore the parameters measured in skin's microcirculation provide representative data on the microcirculation of internal organs.

Currently LDF is the gold standard for the investigation of the microcirculation. The method is based on the Doppler principle. It measures the velocity of the erythrocytes moving within the vessels. Its application is primarily restricted for the research laboratories. Its drawback is that only a tiny piece of tissue (usually below 1 cubic millimeter) can be sampled for microcirculatory assessment. Therefore the measured results are originating from a very restricted sample volume. LDF studies of the arteriolar function have established, that arteriolar microcirculation is under complex regulation.

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 synchronised 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 oxid 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 oxid compounds;

Vessel wall motions in the 0,6–2 Hz and 0,145–0,59 Hz frequency bands can be detected clearly in the arteriolar wall, but with low intensity and they do not play a significant role in the periodic (oscillatory) vessel wall motion, their impact on the microcirculation is negligible *(52, 53)*.

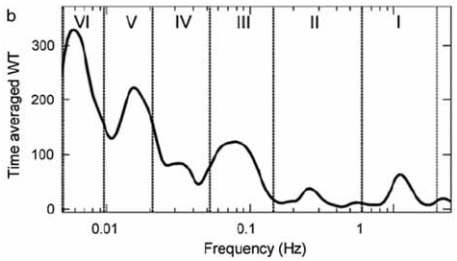

Figure 4. *Time averaged Wavelet Transform as the function of the frequency of vessel wall motion; frequencies are on logarithmic scale (52).*

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 analysed 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 *(55–58)*. 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 *(55)*. Comparative microcirculation assessment was performed in the hand by the same group with LDF and infrared imaging, with excellent agreement between the two methods (Figure 5) *(54)*.

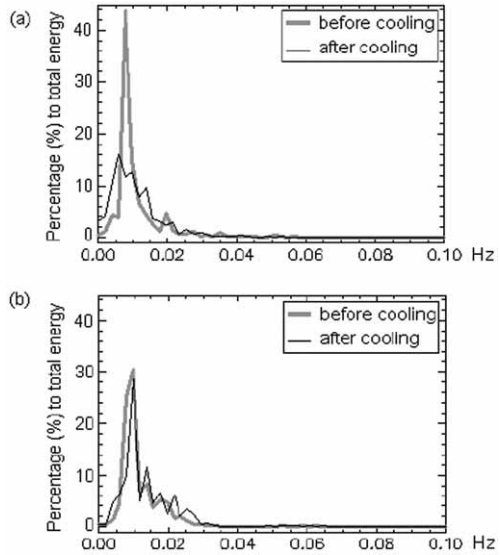

Figure 5. *Dominant oscillatory frequencies by infrared image analysis (left side) and by Laser-Doppler (right side) spontaneously and after a provocation test of cooling (54).*

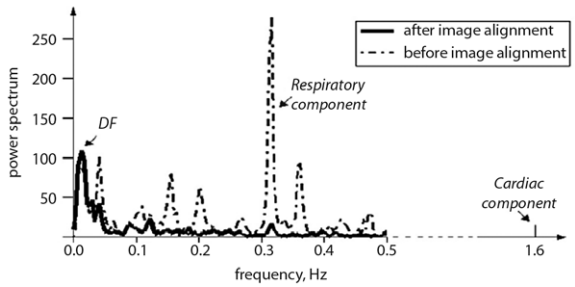

Figure 6. *Power spectrum analysis of microvascular frequencies on kidney surface by infrared imaging; the highest intensity frequency band (Dominant Frequency, DF) is centred around 0.008Hz. Interrupted line with dots represents the raw dataset before image analysis, continuous thick line is the frequency power spectrum after image alignment (55).*

Infrared video thermography as a touchless polygraph method for psychophysiolgical stress detection

Infrared imaging and image analysis has been introduced as a powerful tool for deception detection around 2000 by the demonstration of its ability to detect facial patterns of stress at a distance. Breathing cycle can be monitored by infrared imaging, based on the difference in temperature between the exhaled air and the ambient room temperature. Cardiac pulse wave can also be monitored by infrared thermography in locations, where large arteries travel close to the skin surface (external carotid artery, temporal artery, etc.) *(59–70)*. Replacement of traditional polygraph testing by noncontact infrared video thermograph recordings and their multifaceted analysis makes it possible to test large number of individuals for potential signs of their deceptive behaviour.

CONCLUSION

Infrared image capture and analysis is an outstanding technology that allows non-contact, non-invasive investigation of biological systems, both in preclinical research settings and in the clinical assessment of patients. The investigated object is not exposed to any harmful radiation or other interventions, and therefore infrared imaging can be considered as one of the few truly green imaging technologies with great potential for widespread use both in different specialties of clinical medicine and in research settings.

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