Modalities and Clinical Applications of Dynamic Infrared Imaging

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Abstract – **Dynamic infrared imaging (DIRI), the most effective modality of dynamic area telethermometry (DAT), involves the acquisition of hundreds to thousands of consecutive thermal images, deriving information from the modulation of temperature and of thermal spatial distribution of small subareas. Four groups of clinical applications of dynamic infrared imaging are reviewed from the standpoint of their data processing following FFT analysis of temperature modulation and modulation of perfusion of the cutaneous capillary bed. These include: 1. Visual assessment of spatial abnormalities in perfusion kinetics that can be used in diagnosis of joint disease and of advanced cancer, as well as visual identification of abnormalities in subcutaneous circulation. 2. Objective computerized diagnosis of systemic chronic neuronal disorders that may affect modulation amplitudes and their spatial distribution. 3. Objective computerized detection of cancer, breast and skin cancer in particular, by their effect on the spatial distribution of attenuated subareas at specific frequencies of modulation. 4. Objective assessment of transient mental stress (psychological testing) and of exposure to neurotoxic agents that may affect modulation amplitudes and their distribution over limited periods of time. Following time-dependent changes in temperature modulation at specific frequencies one can assess the severity of functional perturbation of the autonomic nervous system.**

Keywords – **Visual diagnosis; objective diagnosis; computerized diagnosis; cancer; autonomic nervous disorders; joint inflammation; neurotoxic agents; mental stress; lie detection.**

I. INTRODUCTION

Perfusion dynamics of tissues and hemodynamics of the cutaneous capillary bed (CCB) can be monitored and quantitatively assessed following temperature modulation measured by dynamic infrared imaging (DIRI) above 8 mμ.[1] DIRI has been made practical with the advent of fast, highly sensitive focal plane array (FPA) detectors, such as quantum-well infrared photodetectors (QWIP).[2,3] Modulation of skin temperature at frequencies above 0.1 Hz unequivocally manifest modulation of tissue perfusion, because under normal conditions in a clinical setting blood is the only heat supply or sink modulated at those frequencies. Study of the dynamics of infrared emission by human skin is a subset of medical dynamic area telethermometry (DAT).[1] DAT includes physical methods that can measure changes in tissue temperature non-invasively. These include MRI, laser Doppler, tissue impedance, or ultrasound, in addition to DIRI. Among the different DAT methods, monitoring of blackbody radiation is still the simplest and most precise methodology currently available.[3] Among those techniques, DIRI is unique in allowing assessment of cutaneous microcirculation dynamics by measuring the time dependence of spatial variance of temperature,[3] in addition to measurement of the time dependence of tissue perfusion,

Since blood flow is a directional process, which can be assessed by DIRI only under special conditions,[4] one prefers to use the term "perfusion" to describe the bulk phenomena measured by DIRI. The term "hemodynamics" refers to temporal changes in vascular tone as well as transient capillary shunting.

All DIRI applications involve accumulation of hundreds to thousands of consecutive thermal images followed by quantitative analysis of the time profiles of temperature of each pixel or group of pixels.[3,5] In addition to determining the thermal spatial homogeneity of small subareas,[3,6] the two most common analysis procedures are: 1. Determination of the rate of temperature change (rates of warming or cooling, calculated from d(logT)/dt slope, where T = temperature, t = time); and 2. Fast Fourier transformation (FFT) of the time profiles of temperature. Since temperature modulation manifests corresponding modulation of perfusion, FFT analysis yields the relative contributions of different physiological or pathophysiological processes to perfusion dynamics. FFT of the time series of the spatial homogeneity data provides information on the underlying physiological hemodynamic processes that take place in the CCB.[3] Temperature modulation and modulation of the spatial homogeneity are often coupled, and then they are out of phase.[3,6]

Since slow warming or cooling of skin are affected by the environment, while the FFT data reflect physiological cardiac and neuronal functions, in addition to normal and pathological anatomical features of blood supply,[1] the spatial distribution of FFT data is the main source of clinically useful information derived from DAT studies. FFT analysis allows distinction between cardiogenic modulation of perfusion by heart-driven pulsation of blood and autonomic neuronal modulation of vascular tone, which is manifested in corresponding modulation of perfusion. FFT analysis enables also to identify anatomical features of local blood supply, including pathological hypervascularity and vascular occlusions. This paper describes different modes of treatment of the FFT data depending on the clinical application.

II. VISUALIZATION OF LOCALIZED ABNORMALITIES IN TISSUE PERFUSION

The most straight forward clinical application of DIRI is confirmation of thermal anatomical abnormalities that are also detectable by static infrared imaging.[1] These include two

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Abstract

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classical permanent hyperthermal conditions: Chronic joint inflammation, associated with local vasodilatation and consequent attenuation of temperature modulation,[7,8] and localized pathological hypervascularity, which is associated with abnormally enhanced temperature modulation, especially in the cardiogenic range 0.7 to 2 Hz. On the other hand, occlusive disease will result in local hypothermia together with attenuated temperature modulation.[1] These three conditions generally manifest a weak frequency dependence of temperature modulation. In diagnostic use of DIRI, this lends itself to bitmap display of distribution of the mean amplitudes of temperature modulation in a relatively wide range of FFT frequencies over the area of interest.[5,9] The anatomical shape and spatial extent of the abnormal modulation and its average amplitude can be helpful in assessment of the severity of the condition and be used in assessing the efficacy of treatment.[7,8]

Certain advanced cancerous conditions, associated with local hypervascularity and/or inflammation, can be visualized in such bitmaps. However, in spite of selecting a subset of modulation frequencies instead of observing aberrations in gross temperature distribution, this approach can hardly be advocated as a sensitive or specific method of cancer detection, breast cancer in particular, beyond the limited capability of classic static thermography.[10.11]

Another potential medical applications of DIRI that calls for visualization of the area of interest involves the assessment of propagation of cardiogenic pulses of blood in peripheral vessels.[4] This assessment may be useful in mapping peripheral occlusive disease before and after vascular surgery and to diagnose complications in arthro-venal shunting in patients undergoing hemodialysis. Such a test would be faster and as precise as in using Doppler ultrasound.

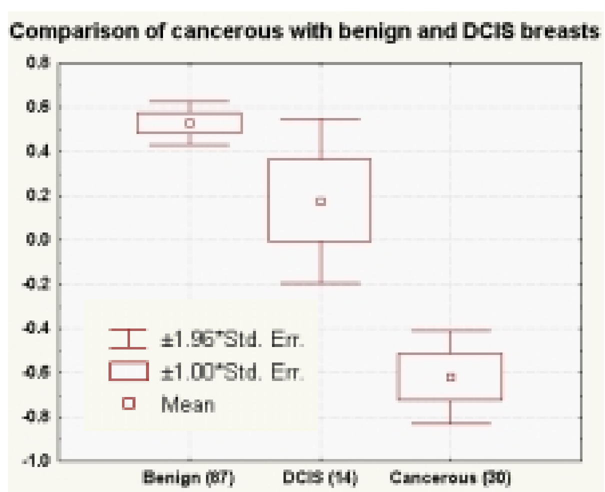
Dynamic imaging allows also detection of localized attenuation of temperature and micro-homogeneity modulation that is manifested only at specific frequencies. These frequencies may slightly differ from one individual to another or change over time in the same individual. Visualization of bitmaps at hundreds of different specific frequencies is obviously impractical. On the other hand, averaging of data over a wide range of frequencies dilutes the information with data of frequencies that are not affected by the given pathology, lowering the sensitivity and specificity of the test. Consequently, DIRI requires then the use of computerized data processing.

II. OBJECTIVE COMPUTERIZED DIAGNOSES

Unlike the visualization modality that displays bitmaps of the distribution of pixels or small subareas with abnormal modulation amplitudes, DAT computerized diagnosis extracts from the FFT data specific parameters that meet the needs of particular diagnostic problems. These parameters are then used to objectively determine the probability of an unknown case to be normal or pathological, respectively. This is done by measuring the closeness of the value of the given diagnostic parameter of the unknown case to its means for normal or pathological populations, respectively. In certain situations, this approach can also be used to quantify the degree of pathology and help in assessing the efficacy of treatment and the completion of recovery. There are two types of diagnostic parameters – parameters that measure the numeric distribution of modulation amplitudes at specific frequencies (e.g., the proportion of subareas with amplitudes above or below a certain threshold,[12] and parameters that measure their spatial distribution and identify clusters of subareas with abnormal amplitudes.[13]

An important group of applications of this modality of DIRI is in the diagnosis of chronic changes in the autonomic nervous system. Under these clinical conditions the pathological systemic changes in the FFT spectra are not time dependent, but they may, like in the cases of cold finger syndrome, Raynaud's Syndrome, or backpain, affect the spatial distribution of aberrant modulations. This pathology could be diagnosed objectively using algorithms similar to those used earlier in objective cancer diagnosis,[12] which did not utilize the changes in spatial distribution of the frequency dependent attenuation.[13] Unlike the case of cancer, the anatomic manifestations of chronic nervous disorders are well defined and do not call for localization *de novo* of a pathological lesion.

The detection of cancerous lesions by quantitative DIRI is another highly attractive application of DAT. Cancerous lesions induce localized attenuation of temperature modulation at specific frequencies. This is caused by vasodilatation induced by cancer-produced extravascular nitric oxide (NO).[13,14] Extravascular NO interferes with the physiological control of vascular tone by the autonomic nervous system.[13,14] Detection of cancer is most effective using parameters that measure the clustering of subareas with attenuated modulation at specific frequencies between 2 and 10 Hz Using this objective quantitative approach one can identify breasts with cancerous lesions with a sensitivity and specificity of >95%.[13 and papers in print] As one can see in Figure 1, the mean value of the diagnostic parameter is about ***plus*** 0.5 for breasts with benign lesions compared with ***minus*** 0.6 for the group of breasts with cancerous lesions. Using zero as a diagnostic



referent value, the test clearly differentiates between these two groups. The technique seems to be less sensitive in identifying breasts with ductal carcinoma *in situ* (DCIS). All 131 breasts studied showed suspicious lesions on X-ray mammography to warrant excisional biopsy. The DIRI test seems to yield significantly higher diagnostic sensitivity and specificity than achievable by any subjective cancer visualization method, including X-ray mammography.[13] Additional studies are needed, however, to evaluate the effectiveness of DIRI in localizing cancerous lesions.

A slightly different modality of DIRI is used in the diagnosis of transient autonomic nervous changes, which occur in response to mental stress or following exposure to certain neurotoxic agents (e.g., choline esterase inhibitors).[1,15] Monitoring of mental stress can be useful in the differential diagnosis of neuroses, detection of drug abuse,[1] and in lie detection.[15] The observed effects will be strongly frequency dependent, and the spatial distribution of enhanced or diminished amplitudes might be significantly affected, because of the anatomy and physiology of the autonomic nervous system. Consequently, these applications call for evaluation of changes in amplitude as function of frequency and of time, as well as changes in their spatial distribution. The rates of change and of recovery can be used to assess the levels of mental stress and/or of the level of exposure to a neurotoxic agent. Unlike the FFT analysis used in the previous applications, which subtracts the low frequency components, in this case one can derive highly useful information also from the low frequency components when in concert with high frequency manifestations. The correlation between temperature modulation and modulation of thermal homogeneity, can yield information on the wash-out rate of the hormone or neurotoxic agent, which is highly valuable in this diagnostic application. The latter information is likely to be useful in triage and treatment of chemical warfare casualties or of personnel exposed to neurotoxic insecticides.[15]

All these computerized analyses are executable on microcomputers that yield a quantitative assessment of the different disorders or dysfunctions with no human intervention. This totally objective evaluation of dynamic thermal imaging data is unique in the field of diagnostic imaging, providing the physician with a rapidly available diagnostic measure that can be readily compared to ranges of normal and pathological values of the given parameter, similar to a CBC or blood sugar analysis.

III. IN SUMMARY

In summary, we have shown that DAT, DIRI in particular, offers a novel diagnostic approach to many different pathological conditions. These include several neurological disorders, cancer, psychological and neurotoxicological problems. We have categorized four different clinical diagnostic modalities of using DIRI. The three quantitative ones, described in Section II. offer unique, fast, objective, fully computerized quantitative diagnostic tests. These utterly non-invasive, relatively inexpensive tests may thus be forerunners of 21st Century medical diagnostic devices, when physiological and biochemical information will be picked up remotely by electronic sensors and then fully interpreted by computers.

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