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Diagnosing Osteoporosis through Numerical Simulation of Bone Sample by Non-Stationary Thermal Wave Imaging

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ABSTRACT
Infrared thermography is an emerging field of interest in diagnosis of various diseases. Osteoporosis is a skeletal disorder of reduced bone strength. A proper diagnosis of this disease further reduces the risk of bone fracture or further damages. In present paper, a bone sample of having different stages of osteoporosis is modeled using finite element analysis and simulated with a Quadratic frequency modulated stimulus. Further FFT phase, pulse compression and random projection transform techniques are employed as post processing schemes for better defect detection and compared their performance with signal to noise ratios.

Key words: Quadratic frequency modulated thermal wave imaging, Osteoporosis, Bone, infrared thermography, Pulse compression, FFT phase, Random projection transform.

1. INTRODUCTION

Osteoporosis is a skeletal disorder causing the reduced bone strength or density. As the age of a person grows, this may leads to risk of fracture. Though it cannot be reversed, early diagnosis helps to maintain good bone strength then avoid unbearable fractures. The nature of homeotherm possessed by human body and thermoregulation of inner core temperature will help to characterize diseases easily. Osteoporosis can be diagnosed based on the different thermal gradients produced in human skeletal structure due to different bone densities representing the stages of the disease. Though the blood perfusion is not considered, the changes in thermal parameters like density, specific heat and thermal conductivity of the diseased portion would be different from the sound region. Osteoporosis can be diagnosed through this basic principle and numerous authors presented their analysis on osteoporosis in biomedical point of view [1-4].

From the first demonstration of infrared thermography for diagnosis of physical illness by Barnes in 1963 [5], infrared thermography became an active research area in biomedical applications due to its safe, non-contact, non-invasive and wide area inspection characteristics. Application of infrared thermography went very pin point to further interests to characterize and diagnose different types of diseases based on infrared thermography. The extensive utilization of infrared thermography is identified in diabetic neuropathy [6], vascular disorder [7], breast cancer detection [8], fever screening [9], brain imaging [10], dry eye syndrome diagnosis [11], gynecology [12] and heart treatment [13]. Signal and image processing techniques incorporated with thermography will help to diagnose and analyze disease as they explore various properties of object under test.

Infrared thermography has its importance in industrial applications with the implementation of pulse [15, 16], lock-in [17], pulsed phase [18], frequency modulated [14] and quadratic frequency modulated thermal wave imaging techniques (FMTWI & QFMTWI) [19-31]. Recent advancement of frequency modulated thermal wave imaging on a bone sample with seven defects modeled using 3D finite element analysis and post processed using Fourier transform based phase analysis to retrieve the relation between relative bone density to relative phase [14]. In present work, the bone sample with different density variations is numerically modeled in COMSOL Multiphysics software using QFM stimulus and corresponding thermal variations are subjected to post processing schemes like FFT phase, pulse compression [20, 21] and random projection transform [22]. Corresponding qualitative analysis provided by thermographic visualization and defect signal to noise ratios.

2. QFMTWI

Non-stationary thermal wave imaging (NSTWI) techniques are gaining wide area of interest from past decade in infrared non-destructive testing (IRNDT). Frequency modulated thermal wave imaging (FMTWI) [14] and Quadratic frequency modulated thermal wave imaging (QFMTWI) [19] techniques comes under category of NSTWI. In QFMTWI [19], a selected band of low frequencies are supplied to modulate the optical stimulus which will heat up the top surface of the sample. The thermal wave generated along the top surface, propagates through the subsurface layers of sample and reflects from the termination end. These reflected gradients provide more heat on the surface. If any defects present in subsurface layers, that portion is more heated due to the time delays produced in the thermal gradients. This can be recorded through an infrared camera. The resultant thermal response is then given for post processing.

The general bio heat transfer equation considering all the arterial, Venus blood vessels, skin, fat and bone is that is widely used Penne's bio-heat transfer equation given by

$$(\rho c)_{tissue}\frac{\partial T}{\partial t}=k_{tissue}\frac{\partial^2 T}{\partial x^2}+(\rho c)_{blood}\,w\left(T_{core}-T\right)+Q_{metabolism} \quad (1)$$

Since the present work omits the considerations of blood perfusion w, temperature difference between core and arterial blood vessels, and the metabolism then the second and third terms in above equation tends to be zero. Then the bio-heat transfer equation modified to be general heat transfer equation with tissue thermal properties as

$$(\rho c)_{tissue}\frac{\partial T}{\partial t}=k_{tissue}\frac{\partial^2 T}{\partial x^2} \quad (2)$$

Can be written as

$$\frac{\partial T}{\partial t}=\frac{1}{\propto}\frac{\partial^2 T}{\partial x^2} \quad (3)$$

Where α=(ρc)tissue/k tissue is the diffusion coefficient, and T is temperature at depth x corresponding to the time instant t. Further Eq. [3] can be solved under boundary conditions with stimulating heat flux at skin surface, the obtained thermal response in Laplacian domain is given by

$$T(x,s)=\frac{Q(s).e^{-\sigma x}}{k\sigma} \quad (4)$$

Where σ=√(s/α) and k is the thermal conductivity. Then the thermal response undergoes 1st order polynomial fitting to eliminate stationary component. Now, the retrieved dynamic thermal response is processed by FFT phase in which each thermal response is transformed into Fourier domain by applying FFT on it. The corresponding phase values are computed and respective phasegrams visualizes the thermal contrast between defective and non-defective regions.

Later a time domain cross correlation named pulse compression is analyzed to detect the time delays between defective and non-defective counterparts [20, 21]. This is employed by cross correlating each thermal response with a reference non-defective thermal profile. Similarly, random projection transform [22] also employed on thermal response which is a statistical method. In RPT, the 3D thermal response is reshaped into 2D and QR decomposition is applied over the 2D data to get orthonormal basis vectors. Further projecting few of these orthonormal basis vectors into data gives random projection components.

3. EXPERIMENTATION

To test the proposed modality, a numerical simulation is carried out in COMSOL Multiphysics software using bio-heat transfer module. Bone sample consisting of skin, muscle and fat each of 0.5mm thickness and a bone of 2.5mm thickness with 7 holes having different density variations. The skin side of the sample excited by a QFM heat flux for 100 seconds with frequency range of 0.01Hz to 0.1Hz. Corresponding thermal response recorded at 25 frames per second. The experimental setup and layout of bone are shown in fig. 1. a and b respectively. Thermal properties of the sample are referred from[14-41].

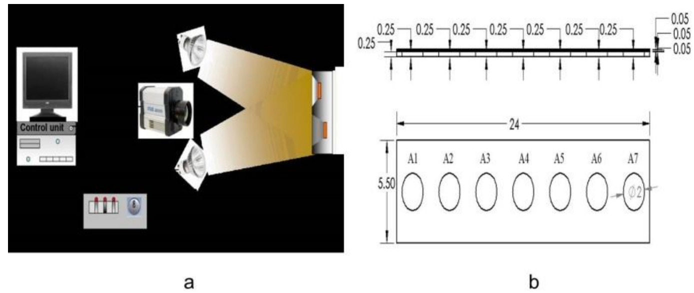

Figure 1: a. Experimental schematic of QFMTWI and b. Layout of Bone sample (all dimensions in mm).

4. RESULTS AND DISCUSSION

The linear fitted and mean removed thermal response and Bartlett windowed thermal response is post processed through FFT phase; Pulse compression and Random projection transform techniques. The observed thermograms are given in fig. 2. a, b and c respectively. From figure, it is clear that the random projection transform distinguishes thermal variations of different bone densities efficiently.

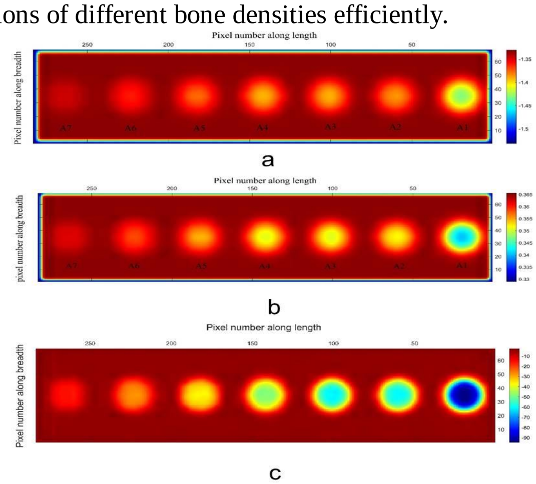

Figure 2: a. FFT phase at 0.017Hz, b. Pulse compression at 18.08sec, c. 1st random projection component.

Further the observed thermal response is characterized by performance metrics like signal to noise ratio. Signal to noise ratio is taken by dividing the difference between mean of defective region to mean of non-defective region by standard deviation of non-defective region[31-35,] as given below

$$SNR(dB)=20\log\left(\frac{\mu_{Defective}-\mu_{Non-Defective}}{\sigma_{Non-defective}}\right) \quad (5)$$

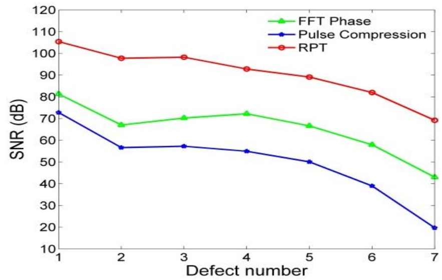

Figure 3:. Signal to noise ratios of different post processing techniques employed on bone sample.

From the observations of thermograms and their respective defect signal to noise ratios, it is concluded that random projection transform provide better results for non-destructive evaluation of biomedical bone sample through QFMTWI.

5. CONCLUSION

The proposed work highlights the capabilities of quadratic frequency modulated thermal wave imaging for detecting density variations in simulated bone sample to characterize the severity of osteoporosis based on density variations. It is clear from the result that quadratic frequency modulated thermal wave imaging in combination with random projection transform based analysis can be used for the early, safe and remote diagnosis of osteoporosis with improved sensitivity and resolution. Along with detection, signal to noise ratios provide better results for random projection transform.

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