Original Article

Dynamic thermal/acoustic response for human bone materials at different energy levels: A diagnosis approach

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ABSTRACT

Background: The non-invasive diagnostic approaches have gained high attention in recent years, utilizing high technology sensor systems, including infrared, microwave devices, acoustic transducers, etc. The patient safety, high resolution images, and reliability are among the driving forces toward high technology approaches. The thermal and acoustic responses of the materials may reflect the important research parameters such as penetration depth, power consumption, and temperature change used for the practical models of the system. This paper emphasizes the approach for orthopedic application where the bone densities were considered in simulation to designate the type of human bones.

Methods: Thermal energy pulses were applied in order to study the penetration depth, the maximum temperature change; spatially and dynamically, and the acoustic pressure distribution over the bone thickness. The study was performed to optimize the amount of energy introduced into the materials that generate the temperature value for high resolution beyond the noise level.

Results: Three different energy pulses were used; 1 J, 3 J and 5 J. The thermal energy applied to the four bone materials, cancellous bone, cortical bone, red bone marrow, and yellow bone marrow were producing relative changes in temperature. The maximum change ranges from 0.5 K to 2 K for the applied pulses. The acoustic pressure also ranges from 210 to 220 dB among the various types of bones.

Conclusion: The results obtained from simulation suggest that a practical model utilizing infra-red scanning probe and piezoelectric devices may serve for the orthopedic diagnostic approach. The simulations for multiple layers such as skin interfaced with bone will be reserved for future considerations.

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1. Introduction

Non-invasive diagnostic approaches have gained attraction in recent years among scientists in the medical community.^{1–7} These enable medical diagnosis with minimum risks, accurate results, and most importantly patient comfort. In some cases, non-invasive approaches are necessary with “undesirable alternatives” for critical surgeries. For instance, in cardiovascular related surgeries, non-invasive diagnostics for coronary disease.⁸

Various bone related diseases may be impacted by various parameters within the skeletal human system. This may include

impact of the fractures in the left or right posterior wall, involving the rim of the acetabulum, with posterior dislocation, the femoroacetabular impingement, the acetabulum (a concave surface of the pelvis, forming the hip joint), may have an impact on the long run on the bone density. In addition, the femoral offset defined by the distance from the center of rotation of the femoral head to a line dissecting the long axis of the femur, may also impact the bone density that may lead to orthopedic diseases. The developmental dysplasia of the hip defined by the Alpha angle may also impact the bone density that may lead to ortho diseases. The study conducted here may assist with monitoring the bone density, designating new development in the above parameters which may lead to orthopedic diseases. Non-invasive approaches may also enable medical progression with medications such as the case of orthopedics. Currently, the non-invasive approaches lack the practical models and methodologies to achieve high level of

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Table 1
Bone material properties.

Tissue	Permittivity	Elec. Cond. (S/m)	Density (kg/m ³)	Heat capacity (J/kg/°C)	Therm. Cond. (W/m/°C)	Heat transfer rate (ml/min/kg)	Heat generation rate (W/kg)
Bone (cancellous)	2.49E+2	9.04E−2	1178	2274	0.31	30	0.46
Bone (cortical)	1.45E+2	2.44E−2	1908	1313	0.32	10	0.15
Bone marrow (red)	9.91E+1	1.04E−1	1029	2666	0.28	135	2.09
Bone marrow (yellow)	3.98E+1	4.71E−3	980	2065	0.19	30	0.46

accuracy and clear medical images. This work presented here is a potential step in this direction.

Non-invasive approaches may require a pattern of the reflected and transmitted power from an energy source such as microwave

energy,⁹ acoustic energy or thermal energy. The control parameters in these modalities are important in the non-invasive approaches.^{10,11} This may include the frequency, penetration depth, the incident power the output temperatures, etc. The

Fig. 1. Sound pressure level.

penetration depth should be long enough to enable the power transmission via the human materials such as bones, skin, blood, etc. Furthermore, the associate diagnostic sensors should be able to determine the change based on the material properties in which the thermal or acoustic energy s propagating through. If the power level is too low, the output may be mixed with thermal noise that is associated with radiation, human skin, etc. In this approach, allowing high level of energy to be applied to the human body will overcome the noise power. High energy pulses will enable practical models to overcome thermal noise when incorporated with this invasive technique. The approach will be advantageous over existing invasive practical models.¹² The proposed method addresses the minimum noise performance and minimum power consumption via solid state sensor devices. The diagnostic approach using EM source has been addressed elsewhere,¹³

however, the acoustic approach should be superior in the sense that it is safer and more desirable for children and pregnancy cases.

2. Mathematical models and methods

The acoustic wave equations used in these simulations are given as follows:

$$\nabla \cdot \left(-\frac{1}{\rho c} (\nabla P_t - q_d) \right) - \frac{k_{eq}^2 P_t}{\rho c} = Q_m$$

where $P_t = P + P_b$, P_b is the bio thermal pressure, P is the acoustic pressure, and

$$k_{eq}^2 = \left(\frac{\omega}{C_c} \right)^2 - \left(\frac{m}{r} \right)^2, \quad C_c = \frac{\omega}{k}$$

Fig. 2. Temperature contour. The horizontal axis gives the r coordinate, while the vertical-axis gives the z -coordinate in mm.

Boundary conditions

$$-n \cdot \left(-\frac{1}{\rho c} \nabla P_t - q_d \right) = 0$$

where m is the mass density, r is the location in space, and ω is the radian frequency. The sound hard boundary equation, matching normal where n is the unit vector normal to the surface. P is the acoustic pressure, c is the speed of sound, ρ is the material density, and k is the wave number.

The Bioheat equations are given as:

$$\rho C u \cdot \nabla T + \nabla \cdot q = Q + Q_{bio}$$

$$q = -k \nabla T$$

$$Q_{bio} \rho_{pb} \omega_b (T_b - T) + Q_{met} + \nabla \cdot q = Q + Q_{bio}$$

where q is the progressing source via the various layers of the materials, Q_{bio} is the bio heat source, T_b is the bio thermal temperature, and P_{pb} is the mass density of the material under bio thermal effect. The effect of the thermo acoustic takes place at the interface between the catheter and the bone material. Therefore, it is important to consider the penetration depth throughout the materials. The drop over the interface is related to the mismatch of the acoustic impedance. The thermal penetration depth is the distance that the heat may travel through. The phonons in the sound possess same characteristics as in heat, therefore, the

characteristic length for the thermal interaction between two media may be characterized by δ given as:

$$\delta^2 = \frac{2kV_m}{\omega C}$$

where K is the thermal conductivity, V_m the molar volume, and C is the molar heat capacity, given at constant pressure.

3. Simulation results and discussions

The four types of bones addressed here were characterized based on their optical, thermal, mechanical, and electrical performances. The bone density was an important factor in designating the bone type or the bone status “in case of bone progression”. The simulation and properties of these materials were based on 1 MHz information. The material properties are actually independent on the frequency except for the electrical properties that may be slightly altered with the frequency. The material properties for the four bone types are presented in Table 1.¹⁴

Four sets of data were targeted in the simulation for the sake of differential diagnostic approaches. It is intended to monitor the acoustic pressure and temperature profile. These data were determined for the four types of bones (Fig. 1).

The following figures are sound pressure level for the four type of bones for energy pulses at 1 s, 3 s, and 5 s (Fig. 2).

Fig. 3. Temperature rise at Acoustic focus vs 0.5 mm off acoustic focus. The horizontal axis gives the temperature rise (K), while the vertical-axis gives the time in seconds.

Table 2

Parameters' comparison between the three energy levels: 1 s, 3 s, and 5 s pulses.

Energy level	Pressure level P_o (dB)	Temperature rise contours (K)	Temperature at source (K)	Temperature at 0.5 mm from source (K)	Temperature change (K)
First level (1 s) for 4 type of bones	215	0.45	1.60	1.15	0.45
	210	0.40	1.50	1.05	0.45
	215	0.49	1.60	1.15	0.45
	220	0.71	2.20	1.60	0.60
Second level (3 s) for 4 type of bones	215	1.69	3.20	2.55	0.65
	210	1.50	3.00	2.35	0.65
	215	1.83	3.40	2.62	0.78
	220	2.63	5.00	3.70	1.30
Third level (5 s) for 4 type of bones	215	4.22	4.30	3.50	0.80
	210	3.82	3.90	3.20	0.70
	215	4.44	4.50	3.60	0.90
	220	6.28	6.50	5.00	1.50

Fig. 4. Practical model.

The following figures are temperature contour for the four types of bones for energy pulses at 1 s, 3 s, and 5 s.

Fig. 3 gives temperature rise at acoustic focus vs 0.5 mm off acoustic focus for the four types of bones for energy pulses at 1 s, 3 s, and 5 s. For the sake of differential diagnosis, the above data is summarized for different energy source and tabulated in Table 2.

4. Elaboration on the simulation results

The above data addresses four types of distinguished parameters: (1) the magnitude of the acoustic pressure, (2) the magnitude of the temperatures, (3) the dynamic performance of the temperature, and (4) the temperature profile including gradient concentration (taken 0.5 mm from the focus of the source). The detection of these four parameters will assist in characterizing the status of human bone density. The thermal and acoustic energy levels are important for the practical models where smart sensors can be utilized to monitor the progression of patient orthopedic disease via non-invasive sensor system. The level of energy should be far from the noise disturbance level in order to enhance the system reliability when measuring such parameters. The energy level is addressed in this study by providing various energy pulse sources applied to the human bone.

5. Conclusion and future work

The above simulations serve as preliminary data to prove the concept of using thermal energy pulses in order to generate acoustic wave and temperature profile “spatially and dynamically” that may support an integrated sensor system that is capable to monitoring the human bone density. A change within 1.5 K is high enough to monitor via IR based sensors.¹⁵ Piezoelectric material¹⁶ may also be utilized for measuring the acoustic vibration within the bone material. The idea of the practical model is shown in Fig. 4 for the illustration of the practical model concept. Piezoelectric

Fig. 5. Micro-electro-mechanical system (MEMS) for acoustic pressure measurement for bone diagnosis.

thin film sensor may also be used for acoustic pressure monitoring. Fig. 5 shows the concept of acoustic pressure measurement. The practical model is reserved for future consideration.

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Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of interest

The authors have none to declare.

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References

1. Ke H, Tai S, Wang LV. Photoacoustic thermography of tissue. *J Biomed Opt.* 2014;19(2):026003.
2. <http://www.pdfdrive.net/current-technology-and-challenges-for-medical-imaging-modalities-e3725189.html>.
3. Capmany J, Li G, Lim C, Yao J. Microwave photonics: current challenges towards widespread application. *Opt Express.* 2013;21(19):22862–22867.
4. El Sayed MJ, Zaghrini E. Prehospital emergency ultrasound: a review of current clinical applications, challenges, and future implications. *Emerg Med Int.* 2013;2013:.
5. Xia J, Yao J, Wang LV. Photoacoustic tomography: principles and advances. *Electromagn Waves (Cambridge MA).* 2014;147:1.
6. Wan Y, Liu D, Ebbini ES. Imaging vascular mechanics using ultrasound: phantom and in vivo results. In: *2010 IEEE International Symposium on Biomedical Imaging: From Nano to Macro.* 2010, April.980–983.
7. Tajbakhsh N, Shin JY, Gurudu SR, et al. Convolutional neural networks for medical image analysis: full training or fine tuning? *IEEE Trans Med Imaging.* 2016;35(5):1299–1312.
8. Celermajer DS, Sorensen KE, Gooch VM, et al. Non-invasive detection of endothelial dysfunction in children and adults at risk of atherosclerosis. *Lancet.* 1992;340(8828):1111–1115.
9. Suryadevara VK, Patil S, Rizkalla J, Helmy A, Salama P, Rizkalla M. Microwave/thermal analyses for human bone characterization. *J Biomed Sci Eng.* 2016;9(02):101.
10. Thella AK, Rizkalla J, Helmy A, Suryadevara VK, Salama P, Rizkalla M. Non-invasive photo acoustic approach for human bone diagnosis. *J Orthop.* 2016;13(4):394–400.
11. Rizkalla J, Suryadevara VK, Thella AK, Helmy A, Salama P, Rizkalla ME. Photo acoustic thermal for human bone characterization: a feasibility study. *J Biomed Sci Eng.* 2016;9(09):445.
12. Mirra JM, Gold RH, Marcove RC. *Bone Tumors Diagnosis and Treatment: Diagnosis and Treatment.* Lippincott Williams & Wilkins; 1980.
13. Steinberg ME, Brighton CT, Steinberg DR, Tooze SE, Hayken GD. Treatment of avascular necrosis of the femoral head by a combination of bone grafting, decompression, and electrical stimulation. *Clin Orthop.* 1984;186:137–153.
14. <https://www.itis.ethz.ch/virtual-population/tissue-properties/database/database-summary/>.
15. Helmy A, Holdmann M, Rizkalla M. Application of thermography for non-invasive diagnosis of thyroid gland disease. *IEEE Trans Biomed Eng.* 2008;55(3):1168–1175.
16. Turner RC, Fuierer PA, Newnham RE, Shrout TR. Materials for high temperature acoustic and vibration sensors: a review. *Appl Acoust.* 1994;41(4):299–324.