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The Development of Therapeutic Ultrasound with Assistance of Robotic Manipulator

Zhen Qiu, Jing Gao, Sandy Cochran, Zhihong Huang, George Corner, Chengli Song

Abstract— **High Intensity Focused Ultrasound (HIFU) is finding increasing application and acceptance as a non-invasive approach to the treatment of targeted malignancy. Despite the wealth of research and interest in HIFU, there are still a number of issues that need to be overcome to extend its clinical applications. These relate to the accuracy of placing the HIFU beam, the ability to visualize the target volume, and the understanding of the beam interaction with tissue. In this paper, the output characteristics of a single element HIFU transducer have been investigated with the assistance of a six-axis modified industrial robot. It is shown in the experimental results that clearly defined thermal or mechanical damage can be produced by changing the parameters of the HIFU. The nature and patterns of damage produced by pre-programmed treatment are now being investigated in tissue.**

I. INTRODUCTION

HIGH Intensity Focused Ultrasound (HIFU) has got growing concern in the treatment of localized malignancy. This kind of therapeutic ultrasound can destroy deep-seated tumors without damaging normal tissue surrounding the tumor [1, 2], and without increasing the risk of distant metastases [3]. It is potentially significant to be an alternative to the traditional open surgery to reduce sufferings as a truly non-invasive modality.

Just as sunlight can be focused down to a spot using a magnifying lens to increase thermal intensity, HIFU is focused on to the tumor deeply seated in human body and the energy carried with the ultrasound beam is converted to heat due to absorption. The temperature reaches its maximum at the focal region, above a threshold of 56 ℃ in 1-2 s, approach 80 ℃ [4], which will consequently cause cell death by thermal coagulation while spare the surrounding or overlying normal tissue [5 - 7].

The lesion caused by HIFU exposure tends to be ellipsoidal in shape typically, with a length of 1 - 2 cm along the beam axis and a diameter of 1 – 3 mm [8]. To cover the entire tumor, it is required that the focal point of HIFU beam should placed side by side and layer by layer generally till the whole required volume has been scanned. During scanning, accuracy, localisation, and repeatability of lesion placement are quite important parameters of avoiding the unpredictable damages to normal tissue. Therefore, a robotic manipulator may be employed as an accurate and precise targeting mechanism [9, 10].

This paper reports on research into issues about the design, development and testing of a reliable HIFU treatment system, especially addresses to improve the treatment accuracy. To allow the focus to be positioned rigidly and precisely, the system under investigation was intended to be configured by an industrial robotic manipulator, which will also make the system reconfigurable to meet the particular needs of location or procedure through its reprogrammable property. Although the complete system could not be used in operating room, its accuracy and feasibility will still provide indications of the usefulness of robotic techniques for implementation with equipments which are directly compatible with the operating room.

A LabVIEW graphical user interface serves as a control centre to define HIFU treatments. This interface sets up the communication network of the HIFU system to connect each element together, and can be used to change and control the HIFU parameters that contribute to the lesion formation.

II. THE HIFU SYSTEM ASSISTED BY ROBOT

This paper describes the development of the robotic HIFU system. The robot RX 90 (STÄUBLI Ltd, Switzerland), applied in this system is an industrial robot with six degrees of freedom. Although not a clinical manipulator, it is very stable, programmable and flexible. Its end effector can be placed in any orientation within the work envelope with ± 0.02 mm repeatability at constant temperature, and an inner counting system is used to return its absolute position [11].

The HIFU treatment system comprises four mainly co-operating modules [12-16]:

1) HIFU-generator module: Composed of Agilent 33220A signal generator, ENI 3100LA power amplifier and a single HIFU transducer with fixed ideal focal length 72 mm and

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operating frequency of 1.09 MHz, produced by Precision Acoustics Ltd.

2) Monitoring and measuring module: Includes Tektronix TDS 2024B oscilloscope, Sonosite 180 ultrasound imaging unit and temperature-measurement unit.

3) Robotic control module: The *STÄUBLI* RX90 robot with its CS7 controller. The motion of this robotic manipulator is controlled by program code in the V+ language.

4)System control module: A graphical user interface written in NI LabVIEW programming language to serve as the computer control centre.

The HIFU transducer was attached to the robot with a specific holder which was designed to replace the conventional robot gripper. The movement of HIFU beam was controlled with the robotic arm by running robot programs, using the V+ language.

A laptop computer was used to serve as the system control centre and communicate with individual components. Serial communication was established between each single and the key HIFU parameters such as the exposure duration were controlled by the LabVIEW program. Measurement data were collected by a special I/O functional node in LabVIEW, and then processed, displayed, and stored.

The experimental sample, optically transparent Poly-acrylamide (PAA) gel phantom, was made for HIFU treatment to visualize the effects of the temperature rise in the focal area and the process of formating a lesion. Liquid fresh egg white was added as a thermal sensitive indicator [17] and degassed water was used as the coupling medium because it transmits HIFU without spatial distortion.

III. ACOUSTIC FIELD MEASUREMENTS

The characterization of the focused field, such as the beam profile and focal length, establishes a set of parameters of great importance to HIFU treatment, and can be estimated through measuring the ultrasonic field [18].

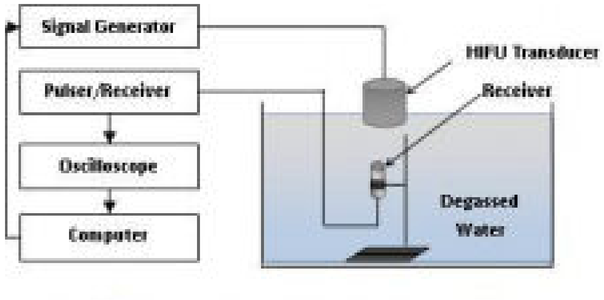


Fig. 1. The system used to measure the ultrasonic field

The measurement system was set up as shown in Fig. 1. The HIFU transducer was attached to the end effector of the robot vertically and immerged into the degassed water, an ultrasonic receiving transducer, with a diameter of 3.3 mm and an operating frequency of 30 MHz, was placed to measure the acoustic energy. Then the signal was amplified through the receive amplifier of a pulser/receiver (DPR 300, JSR Ultrasonics, USA).

The robot arm was controlled by V+ programme code to follow a step-by-step procedure and contribute a 3D matrix in space to measure the acoustic field. The robot carried with HIFU transducer stopped at each step and sent a binary signal to computer, to trigger to start recording the peak-to-peak voltage value measured by the receiver. Four data points were collected at each step and their average was treated as the final data and then stored.

The robotic motion formed here is a 7 x 7 x 36 point matrix in space. There were 7 steps in the x and y directions respectively and 36 layers in z direction (the distance between the surfaces of HIFU transducer and receiver initiated from 50 mm to 85 mm), with each step of 1 mm. Fig. 2 shows the contour map of the focal zone along the axial direction, confirming the value of the measurement, the ultrasonic field did not have as compact a focal zone as expected, and the maximum amplitude i.e. the focal point was obtained at the distance of 67 mm away from the HIFU transducer.

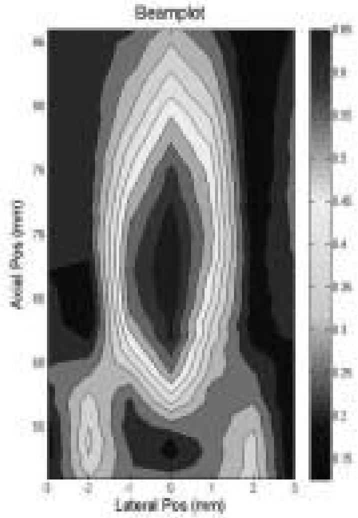
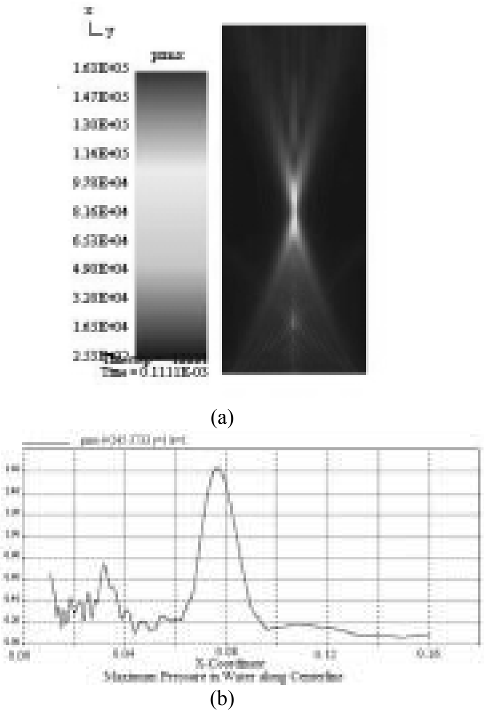


Fig. 2. Contour map of the focal zone in ultrasonic field along the axial direction

2D PZFlex finite element models were generated to estimate the acoustic properties of the HIFU transducer. Firstly, the essential material properties (e.g. physical properties, mechanical properties, dielectric properties, and piezoelectric properties) were specifically determined for each component. Secondly, adequate mesh grid was set to ensure sufficient grid points to sample the model and nodes were specified for electrodes. Moreover, boundary conditions and electric drive were also defined to mimic the exact situation of the 2D slice. Fig. 3 (a) and (b) are the PZFlex simulation results. In Fig. 3 (b), the peak acoustic pressure appears at 75.16 mm in front of the transducer however, this value includes the thickness of transducer's backing layer, which is 4.26mm. Therefore, the actual maximum pressure is at the distance of 70.9mm in front of transducer. By comparing the acoustic field measurement results with the PZFlex finite element simulation results, similarly good agreement was achieved.



(a)

(b)

Fig.3 (a) PZFlex Simulation of HIFU beam; (b) Acoustic pressure in water vs. axial distance graph, includes thickness of backing layer.

IV. TEMPERATURE MEASUREMENT

The fabrication of this PAA gel phantom was based on the research of Kenji Takegami in 2004: 44.5% (v/v) degassed water; 30% (v/v) egg white; 24.8% (v/v) 40% w/v acrylamide; 0.5% (v/v) of 10% ammonium peroxodisulfate; and 0.2% (v/v) of TEMED, which has similar acoustic properties to those of soft tissue, including speed of sound, density, and attenuation coefficient [19].

The temperature rise was recorded by medical thermography in this paper. JADE MWIR camera was placed above the gel phantom with an air path to its upper surface. The HIFU transducer was immersed in degassed water and fixed 67 mm away from the upper surface of phantom. For this reason, the focal point of the HIFU transducer could be easily got just *under* the upper surface of the phantom. The input power of transducer is about 70W, and the intensity of focal zone is approximately 82W.cm^{-2}. The temperature was measured every 50 ms for 30 s exposure time with an extra 30s' cooling time. ALTAIR workstation with relative software provided by Cedip Ltd., and FG9800 digital PCI frame grabber were used for image acquisition and processing.

The correlation between the temperatures at the focal area and time during the whole 60s duration is displayed in Fig. 4. The temperature reached 56℃ in about 4 seconds from the initial phantom temperature of 24℃, and reached up to 66.49 ℃ in about 5.7 seconds, then followed by an interruption of lesion formation. Fig. 5 displays the images captured at 2 s, 10 s, 20 s and 30 s during the exposure time, respectively. The temperature scale is in Celsius.

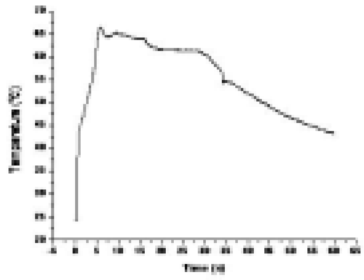


Fig. 4 Temperature vs. time graph of 30 s exposure with an additional 30 s cooling time.

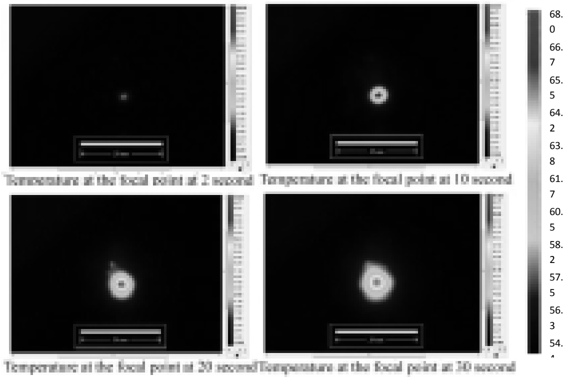


Fig. 5 Medical thermography at the focal point at 2, 10, 20, and 30 s respectively

V. EXPERIMENTS AND RESULTS

Based on the HIFU system assisted by both the robot and LabVIEW, the various experimental parameters were pre-set in program to make sure multiple series of lesions under different experimental conditions can be created in one procedure. Ex vivo experiments were carried out in PAA gel phantom by varying the main parameters i.e. the exposure Fig. 6 shows one series of deep-seated lesions created within phantom by using different exposure durations ranging from 5 to 55 s. Then the phantom was imaged by using a Sonosite 180 medical ultrasound machine. Fig. 7 are the same series of lesions from an overhead view. As can be seen, under the assistance of robot, the lesions have been generated in a straight line with a measured separation of 7 mm as planed.

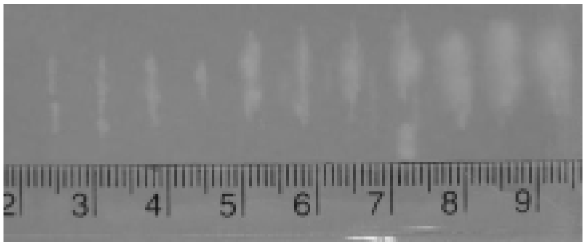


Fig. 6 The lesions generated within phantom under various exposure time from 5s to 55s. Input power of transducer is about 70W.

The experiment aims to examine the extent of thermal ablation on the surface of HIFU phantom was carried out, as can be seen in Fig. 8. The distance between HIFU transducer and upper surface of phantom ranged from 65mm to 80mm by operating programmed robot, with step of 1 mm.

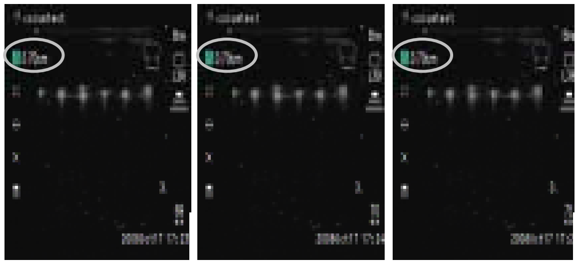


Fig. 7 Lesions in overhead view with the measured distance between adjacent lesions

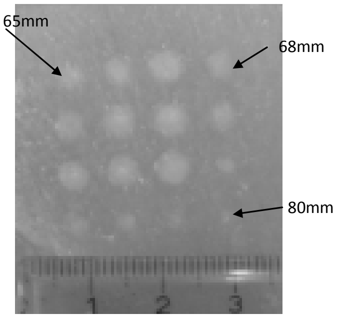


Fig. 8 The thermal lesions on surface of HIFU phantom at varying distance from 65 to 80 mm, Input of transducer is about 70W.

VI. CONCLUSION

A HIFU treatment system assisted by the modified industrial robot (*STÄUBLI* RX 90) was first described in this paper. Experiments with PAA gel phantoms were conducted to test the feasibility of this robotic assisted HIFU system and the effects of HIFU treatment. Ultrasound (HIFU) beam profile and temperature change were specially investigated to fully understand the principles of HIFU treatment through thermal ablation. The main conclusion of this investigation is that HIFU thermal ablation can be successfully applied with the assistance of the robot and other hardware under computer control.

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