論 文 の 内 容 の 要 旨

論文題目

Focal spot localization and intensity estimation of

high-intensity focused ultrasound therapy using ultrasound imaging

(超音波撮像を用いた高強度集束超音波治療の焦点定位および強度推定)

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High-intensity focused ultrasound (HIFU) therapy is a revolutionary, truly noninvasive physical therapy, in which localized ultrasonic energy is accumulated to ablate tumors without the need for surgical incision. The clinical benefits of HIFU therapy include less postoperative pain, reduction of hospitalization down to one day, and operation repeatability. In biological tissues, however, the HIFU beam may be strongly attenuated, or may even focus outside the desired target region due to acoustically heterogeneous tissue having different ultrasound propagation properties (e.g., muscle, skin or fat), or due to uncontrollable experimental parameters (acoustic coupling at the interface of the ultrasound source, anatomical barriers such as bones, gas). These tissue heterogeneities and experimental parameters are difficult to quantify accurately and precisely a priori, and cannot be completely accounted for during calculation of the focusing parameters. This surgical procedure “blindness” increases risks of applying the HIFU energy and thus creating a therapeutic effect (e.g., thermal lesion) at a wrong position inside the medium, which potential deleterious consequences on the efficacy, accuracy, and safety of the treatment.

In light of the above, this thesis aims to develop a surgical "microscopy" technique that can provide surgeons with reliable estimators of HIFU focal spot location and intensity using ultrasound imaging before and during treatment. Specifically, the following three independent methods were proposed and evaluated:

1) *HIFU focal spot localization by means of backward reconstruction of transmitted acoustic wave field using beamforming in an ultrasound scanner*: The concept underlying the proposed method is time reversal for reconstruction of transmitted acoustic wave field. The novelty of this method lies in its implementation of time reversal via beamforming in an ultrasound scanner, which allows for easy, simple, and real-time imaging of ultrasound wave field. The feasibility of the method was evaluated in a lossless medium with and without HIFU beam aberrations. The root-mean-square error of estimated HIFU beam profile was 17.6% in the existence of the aberrations. Thus, the results indicate the feasibility of the method, although reconstruction errors were observed, arising from the finite aperture size of the probe serving as time-reversal mirror (i.e., receiver) or from long path length from the source. Despite this limitation, the proposed method may be acceptable as an easy, simple, and real-time HIFU focal spot localization technique used for therapy guidance if the HIFU source and its receiver can be located in a proper face-to-face orientation.

2) *HIFU focal spot localization by means of backscattered acoustic wave field reconstruction with a suppression of inhomogeneous backscattering*: In order to improve the accuracy and precision in localizing HIFU focal spot in an ultrasound pulse-echo image, named HIFU beam imaging (HBI), the image deterioration due to backscattering inhomogeneity of the biological tissues were suppressed by the proposed algorithm. First, the rationale for the development of HBI was confirmed by simulations of the difference between HIFU and imaging beam aberrations in heterogeneous propagative medium. Then, the proposed algorithm is introduced on the basis of an inverse problem approach to retrieve HIFU beam components from measured backscattered HIFU echoes while simultaneously suppressing the backscattering components. An overdetermined problem was formulated by means of a line scan of the HIFU focal spot and solved using a nonlinear least-squares method. The

proposed algorithm was validated in ex vivo experiments involving focal position shifts and beam width variations, which were induced by phase and aperture control of HIFU phased arrays. The accuracy in estimating the focal position shifts were within a 1 mm error, and the accuracy in estimating the beam width variations could be improved within a 2 mm error by taking into account the point spread function of the image. Thus, the proposed method significantly improves HIFU echo image quality, which is invaluable for localization of the HIFU focal spot.

3) *HIFU intensity estimation using localized displacement induced by acoustic radiation force*: The estimation method of the local intensity at the HIFU focal spot was proposed by combining measurement of the displacement induced by acoustic radiation force and simulation of viscoelastic dynamics. The proposed method was verified in phantom experiments mimicking the mechanical properties of biological soft tissues. The result of estimation error between the true intensity and estimated intensity at the focus was 5.7 ± 3.6%, indicating that estimated *in situ* local intensity using the actual measurement provide surgeons with reliable information to predict the thermal dose before exposing the HIFU beam on the targeted tumor.

According to the results of the thesis, the proposed methods were successful in focal spot localization and intensity estimation within an acceptable range in phantom or ex vivo experiments. I believe that proposed methods discussed in this study would be invaluable in developing methods for predicting thermal dose amounts to improve the efficacy, accuracy, and safety of HIFU therapy.