Improved highly accurate localized motion imaging for monitoring high-intensity focused ultrasound treatment
集束超音波治療のための局所振動イメージングの高精度化

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1. Introduction

High intensity focused ultrasound (HIFU) was proposed to be a minimally invasive treatment modality for cancerous tumors. It could produce irreversible tissue thermal coagulation from outside of body. For the treatment, monitoring is extremely important and Magnetic Resonance Imaging (MRI) is currently employed for it. However, MRI is not only expensive but also low temporal resolution, thus ultrasound monitoring method is under investigation [1].

Our group had developed a HIFU real-time feedback control system with an ultrasound monitoring method which is Localized Motion Imaging (LMI) [2]. Tissue stiffness increases after coagulation and LMI could detect the change of stiffness. However, our previous LMI wasn't robust to noise. In this study, three techniques are proposed to improve the previous LMI.

In this study, three techniques are proposed to improve the previous LMI, including dynamic cross correlation window, vibration-frequency band pass filter and maximum vibration initial selection techniques. The improved LMI using these techniques has higher accuracy and robustness than the previous LMI.

2. Method

2.1 Previous Localized Motion Imaging
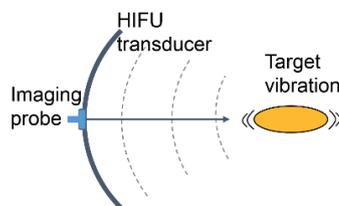
Fig. 1 HIFU treatment with LMI monitoring

LMI is a technique to detect the change of tissue stiffness caused by its thermal coagulation in HIFU treatment. **Fig. 1** shows the schematic diagram of HIFU treatment with LMI monitoring. Acoustic radiation force of HIFU causes the target tissue vibration and deformation with tens of μm. Imaging probe detects the deformation using A-scan lines obtained in different time. The coagulation area is estimated by the decrease ratio of deformation amount.

To detect the deformation using A-scan lines, the cross correlation with phase information are employed. By this method, the similarity of cross correlation can be expressed as:

$$C(n) = \frac{\sum_{m=1}^{M}[(I(m,k)-\bar{I})\times(I(m+n,k+1)-\bar{I})]}{\sqrt[2]{\sum_{m=1}^{M}[I(m,k)-\bar{I}]^2 \sum_{m=1}^{M}[I(m+n,k+1)-\bar{I}]^2}} \quad (1)$$

where, I denotes obtained A-scan lines, m and k are depth and frame of the A-scan lines. M denotes the window size of cross correlation. After obtaining the similarity, the deformation p equles to n, which makes $C(n)$ maximum. To improve the accuracy and use the phase information, autocovariance is calculated by:

$$AC(n) = \sum_{m=1}^{M}[(I(m,k) - \bar{I}) \times (I(m+n,k) - \bar{I})] \quad (2)$$

then the deformation with phase information can be expressed by:

$$s = p - \frac{f_s}{2\pi f_c(2w+1)}\sum_{i=p-w}^{p+w}[\arg(C(i)) - \arg(AC(i))] \quad (3)$$

where, f_s and f_c are the sampling frequency of the imaging probe and the central frequency of its transmitted wave. $\arg(C(i))$ and $\arg(AC(i))$ are argument of $C(i)$ and $AC(i)$ which are complex number, since A-scan line signal (I) is complex number after bandpass filtering.

2.2 Proposed techniques for impvement

In this study, three techniques are proposed to improve the accuracy and robustness of the previous LMI.

First, dynamic cross correlation window is proposed. In the cross correlation (Eq. (1)), window size (M) is important, too small window size decreases noise robustness, and too large causes low spatial resolution of vibration map (**Fig. 2(a)**). As a compromise, 64 was used in the previous LMI. However, as the depth increases, the signal to noise ratio (SNR) decreases, for the deep region, 64 was too small, thus the previous cross correlation was not robust to noise. In the proposed dynamic cross correlation, the window size is initially set as 64, but if the similarity is smaller than a threshold (0.8), the

window size will be increased until it larger than the threshold.
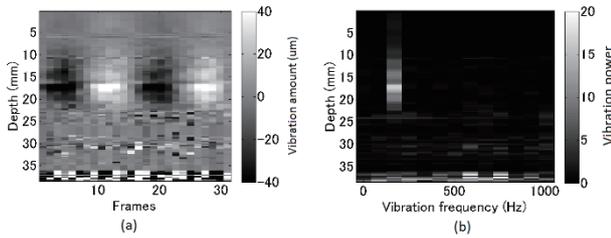
Fig. 2 Vibration map and its fourier transform.

Second, a novel vibration-frequency band pass filter is proposed. In each second, 26 frame A-scan lines are obtained, which includes two circles of vibration. **Fig. 2(a)** shows the vibration map of these A scan lines. To obtain the vibration amount in each second, the previous method calculates root mean square (RMS) of the vibration map in different depth. The RMS involves vibration power from any frequency. Instead of this, the proposed method applies fourier transform to each depth and get the vibration amount (**Fig. 2(b)**) for each frequency, then vibration amount of 168 Hz is used as the vibration amount in this second, because the frequency of acoustic radiation force is 168 Hz.
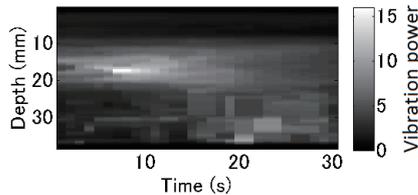
Fig. 3 vibration amount map in each second

Finally, maximum vibration initial selection is used. To calculate the decrease ratio of vibration using vibration amount map (**Fig. 3**), the initial vibration amount have to be selected. The previous LMI employed the vibration amount in the first second. However, although temperature increases, the stiffness of soft tissue may decrease before coagulation [3], and the vibration amount in the first second is not always maximum. Therefore, the proposed method selects the maximum vibration amount as the initial vibration amount, which is in the 8th second in **Fig. 3**.

3. Results

To quantitatively compare the previous LMI and the improved LMI with the three techniques, we prepared 49 data set which were obtained with different initial temperatures and exposure times. The initial temperatures were 10, 20 and 30℃, and the exposure times are 15, 20, 30, 35 and 45s. The mean actual coagulated size is 8.59 mm, measured after cutting coagulation volume out. **Fig. 4(a)** and **(b)** shows the results of the previous and improved LMI, respectively. The horizontal and vertical axes are measured coagulated size and estimated that by

LMI, respectively. The data points is closer to the dotted line, the estimation error is smaller. Thus, the improved LMI shows higher accuracy than the previous LMI. Furthermore, the root mean square error (RMSE) of the previous LMI are 2.51 mm, and that of the improved LMI is 1.71 mm.
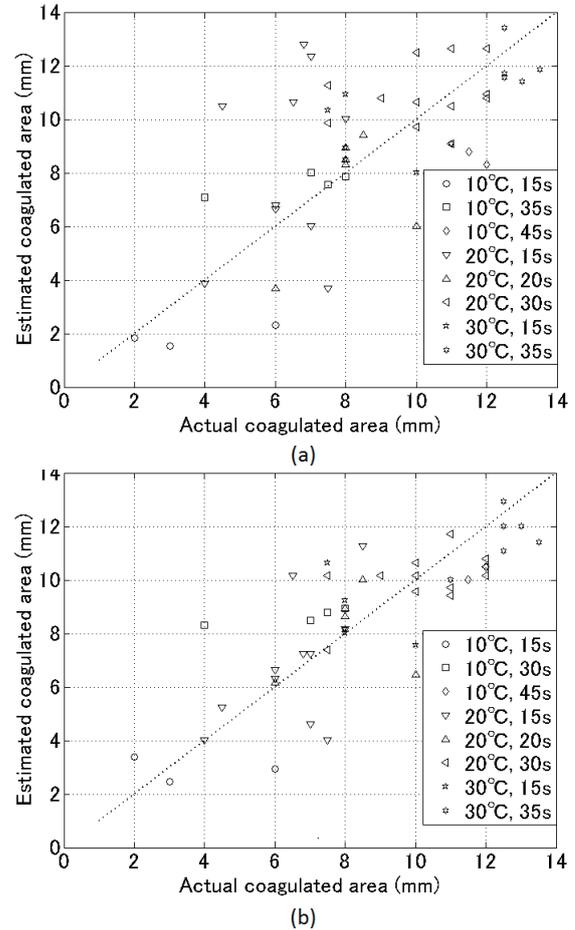
Fig. 4 Results of (a) previous LMI and (b) impvoed LMI

4. Conclusion

In this study, an improved LMI with three novel techniques is proposed. The quantitative evaluation shows the improved LMI decreases RMSE from 2.51 to 1.71 mm for 49 data set with 8.59 mm average coagulated size.

References

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