論文の内容の要旨

論文題目：Ultrasound imaging and analysis by tissue acoustic property estimation

（組織の音響特性推定による超音波画像イメージングおよび解析に関する研究）

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Introduction

Conventional clinical ultrasound imaging system assumes a pre-determined constant sound propagation speed, mostly 1540 m/s, in human soft tissue for the design of beam forming delay patterns. However, there are actually different sound speeds in different soft tissues. The mean values for different tissues range from 1420 m/s in breast fatty tissue up to about 1640 m/s in certain muscle tissue [1]. The mismatch between assumed and real sound speeds results in two potential degradations [2] in ultrasound image. A potential degradation is the spatial shift in ultrasound image because the assumed sound speed is used to calculate the distance between target and transducer. The other is the defocus of ultrasound image because both receive and transmit beam forming delay patterns are designed using the assumed sound speed. Sound speed estimation is not only can be used for improving imaging but also can be used for diagnosis. Even for same tissue, disease may cause different sound speeds. For example, sound speed of fatty liver is lower than normal liver. Thus, sound speed estimation not just can improve the quality of ultrasound image but also provide important diagnosis information.

There are various methods already proposed for sound speed estimation. Robinson et al. classified these methods into transmission and pulse-echo methods by principle [3]. Transmission methods measure sound wave propagation time between transmitter and receiver. Pulse-echo methods estimate sound propagation speed by processing pulse-echo data obtained from one or several ultrasound transducers. However most of them require multiple apertures or complex computation.

In this thesis, an average sound speed estimation method basing on lateral similarity focus quality factor is proposed. This method can estimate average sound speed for both homogeneous and two layer structures by finding the best focus quality ultrasound images formed by different assumed sound speeds. Furthermore, the possibility of fatty liver diagnosis using proposed method is proved by *in vitro* experiments for both fresh animal normal liver and fatty liver. Since homogeneous assumption, proposed method may be not stable to complex inhomogeneous structure. The performance of proposed method is under complex inhomogeneous structure is evaluated quantitatively by using PZFLex simulation. In this thesis, there are five chapters.

Sound speed estimation method

An average sound speed estimation method is proposed in this thesis using lateral similarity focus quality factor and basing homogeneous or multi layers homogeneous assumption. The lateral similarity can measure lateral speckle size. The presence of speckle is an inherent characteristic of medical ultrasound image. Speckle is formed as a result of the interference between echoes from nearby scatters. Since the speckle in ultrasound image is the convolution of point spread functions (PSFs) and scatterer reflectivity in complex plane with a random phase, the speckle size depends on PSF size. Thus lateral similarity can evaluate PSF size and focus quality. There are three steps in proposed method including receive beam forming, focus quality evaluation and iteration.

Firstly, different focus quality image can be formed using different assumed speeds. The PSF size will become larger when the sound speed mismatch increases since electronic focusing techniques are employed in most ultrasound imaging systems. In these techniques, both transmit and receive time delay patterns are designed to confirm that sound beam can focus on plan focus point. And they can be calculated as following,

$$t_{delay}(n) = \frac{\sqrt{F^2 + [(n-(N+1)/2)d]^2} - F}{v} \tag{1}$$

where F is planned focus depth, N is number of active elements, n ranges from 1 to N, d is the center to center distance between adjacent elements and v is the sound propagation speed. As last equation shown, sound speed is an important parameter to calculate time delay patterns. If the sound speed mismatch increases, the time delay pattern error will become larger and sound beam will become wider in the plan focus depth. Thus the PSF size will become larger when the sound speed mismatch increases.

Secondly, the normalized acutocovariance function (NACVF) is employed for focus quality evaluation. Since NACVF can quantitatively evaluate speckle size, which depends on PSF size. It is able to evaluate PSF size and focus quality. Its expression can be written as following,

$$NACVF(x,z) = \frac{1}{N}\iint_{ROI} dudv\,\frac{[e(u+x,v+z)-\bar{e}][e(u,v)-\bar{e}]}{\sigma^2} \tag{2}$$

where ROI is the "region-of-interest", $\bar{e}$ is the mean value of ROI, (x, u) and (z, v) are the lateral and axial coordinates, respectively. The NACVF in lateral direction is used to evaluate focus quality since PSF size in lateral direction is sensitive. Fig.1 shows lateral NACVFs of three images, which are formed by same pre-beam formed RF data using different assumed sound speeds. In this thesis, the average NACVF (ANACVF) of useful lateral shifts is employed to quantitatively evaluate focus quality of ultrasound image. The effect of noise can be reduced since average value of NACVFs of useful lateral shifts is used. Useful lateral shifts include all lateral shifts less than the maximum useful lateral shift. The maximum useful shift is decided by three steps. Firstly, the sound speed in the middle of the possible speed range is selected. Secondly, the NACVF curve of ultrasound image formed by the selected speed is calculated. Finally, if there is rebound before 30 lateral shifts, the rebound shift position is the maximum useful shift. If there is no, the maximum useful shift is 30.

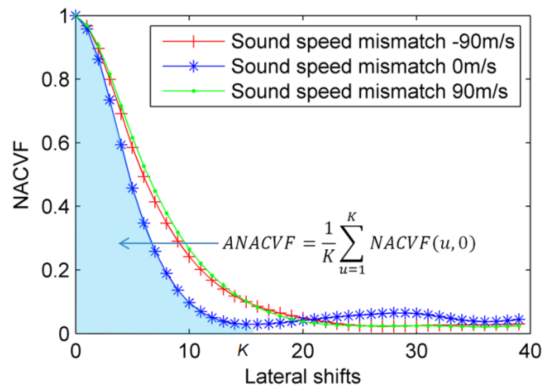

Fig. 1 NACVFs of ultrasound images

Thirdly, Newton's iteration method is employed to find the best focus quality ultrasound images formed by different assumed sound speeds fast. Ultrasound image reconstruction times for sound speed estimation can be reduced obviously comparing to brute force method.

Evaluation

Performance of proposed method is evaluated quantitatively by both simulations and experiments. The evaluation includes homogeneous simulation, homogeneous and two layer phantom experiments, homogeneous and two layer in vitro experiments and complex inhomogeneous simulation. Firstly, homogeneous simulations are implemented by suing Field II simulation program. They show that absolute estimation errors of proposed method are 22.92±17.46 m/s (1.49%±1.13%), 4.57±2.83 m/s (0.30%±0.18%), 2.76±1.68 m/s (0.18%±0.11%), 1.50±0.87 m/s (0.10%±0.06%), 1.30±0.66 m/s (0.08%±0.04%) and 1.10±0.63 m/s (0.07%±0.04%) for ultrasound data obtained by 30, 50, 70, 90, 110 and 130 individual active elements, respectively and the performance of proposed method is obviously better than previous image registration and brightness methods. Secondly, homogeneous and two layer phantom experiments are implemented by using a homogeneous gel phantom and canola oil. They show absolute estimation errors of proposed method are 3.78±4.50 m/s (0.25%±0.30%) and 6.77±4.75m/s (0.45%±0.31%) for homogeneous and two layer phantoms, respectively. Thirdly, homogeneous and two layer *in vitro* experiments are implemented by using fresh normal liver, fresh fatty liver and canola oil.

Homogeneous *in vitro* experiments show absolute estimation errors of proposed method are 5.59±5.68 m/s (0.36%±0.37%) and 6.93±3.57 m/s (0.47%±0.24%) for fresh normal and fatty livers, respectively. Two layer in vitro experiments show absolute estimation errors of proposed method are 8.79±4.08 m/s (0.57%±0.36%) and 9.79±3.75 m/s (0.66%±0.25%) for normal and fatty livers, respectively. Fourthly, complex inhomogeneous simulations are implemented by using PZFlex simulation software. They show that as the speed difference between background and inhomogeneous regions, the diameter of inhomogeneous regions and the percentage of inhomogeneous regions in sound field increase, the performance for proposed average speed estimation method decreases.

Discussion

In this thesis, an average sound speed estimation method is proposed and evaluations show its performance in both homogeneous and complex inhomogeneous structure and its possibility for fatty liver diagnosis. However, there are still several interesting future works for this study. First, performance of proposed method decreases when inhomogeneous region diameter increases since refraction. For large inhomogeneous region, refraction should be considered in receive beam forming for improving performance. Second, complex inhomogeneous simulation study just considers two dimension structure, but vivo tissue is three dimensions. Thus, three dimension complex inhomogeneous simulations will be an interesting future work. Third, all depth of ultrasound image is employed for focus quality evaluation, but defocusing of transmit focus depth is not sensitive to sound speed mismatch. Thus, different depth ultrasound image may be given different weight in focus quality evaluation for sound speed estimation. Fourth, ultrasound image analysis including segmentation and registration is heavily dependent on image quality. Ultrasound image analysis may be improved by using high quality ultrasound images formed by estimated sound speed.

Conclusion

In this thesis, there are mainly three contributions. First, an average sound speed estimation method is proposed by using lateral similarity focus quality factor. Second, fatty liver diagnosis possibility of proposed method is proved by using *in vitro* experiments. Third, performance of average sound speed estimation method under complex inhomogeneous is quantitatively evaluated.

Reference

1. Duck F (1990) Physical properties of tissue : a comprehensive reference book. Academic Press
2. Anderson M, McKeag M, Trahey G (2000) The impact of sound speed errors on medical ultrasound imaging. Journal of the Acoustical Society of America 107:3540-3548
3. Robinson DE, Ophir J, Wilson LS, Chen CF (1991) Pulse-echo ultrasound speed measurements: Progress and prospects. Ultrasound in Medicine & Biology 17 (6):633-646