Real-time Tissue Elasticity Imaging using the Combined Autocorrelation Method

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Tissue elasticity imaging is expected to be a new technique for diagnosis of tissue disease such as cancer. As conventional ultrasound examination, freehand manipulation of the probe and real-time visualization are required for a practical system of tissue elasticity imaging. Various techniques for this type of imaging have been proposed for more than 10 years, but until recently no method has been developed to a practical level. We developed the Combined Autocorrelation Method (CAM), which produces an elasticity image with high-speed processing and high accuracy. Moreover, the method is suited to free-hand compression due to wide dynamic range for strain estimation and robustness for lateral movement of tissue. We achieved a real-time tissue elasticity imaging system based on its algorithm using a commercial ultrasonic scanner. The developed method was applied to breast disease diagnosis *in vivo*. The results demonstrate that the system can provide high-quality and stable elasticity images in clinical measurement and the tissue elasticity image enables us to achieve more precise diagnosis based on simple diagnostic criteria.

Key Words: Tissue Elasticity Imaging, Combined Autocorrelation Method, Strain Mapping, Tissue Characterization, Cancer Diagnosis

1. Introduction

Ultrasound tissue elasticity imaging is expected as means for providing novel diagnostic information for tissue disease such as cancer since the tissue hardness is closely related to its pathological state[1)]. Therefore, many investigations on imaging tissue elasticity by ultrasound have been carried out from the 1990s. Ophir et al.[2)] began the study which images strain distribution under the static tissue compression, and Parker et al.[3)] proposed another method which images propagation velocity distribution of shear wave produced by mechanical vibrator. The former is categorized into static methods and based on the fact that hard tissue has a small strain. The latter is referred to as dynamic methods and using the fact hard tissue has a high propagation speed. Due to some merits such as high spatial resolution and easy implementation, the static methods are now mainly investigated.

Advantages of ultrasonic examination such real-time and simple operation should be preserved in the elasticity imaging system. Although different approaches for static methods have been proposed in the last decade, it was not so easy to satisfy real-time operation and freehand manipulation of probe which can be used clinically[2)-5)]. A high-speed algorithm for estimating strain distribution and processing with hardware are required for real-time measurement. Regarding simple operation, freehand manipulation of the ultrasonic probe such as in the case of conventional ultrasonic diagnosis is desirable. However, initially, tissue compression for elasticity imaging was performed using the stepping motor attached to an ultrasonic probe for an accurate compression in the axial direction.

Therefore, we developed a new method (CAM)[6)7)] which satisfy these conditions and recently released a commercial ultrasound scanner for real-time tissue elasticity imaging by implementing the CAM algorithm with cooperation

with Hitachi Medical Corporation. The echo signals are captured in real-time while the probe compresses or relaxes the body through freehand operation. The Strain images are superimposed on B-mode images with a translucent color scale. Results of clinical evaluation of developed system demonstrated the high potential of the elasticity image for breast examination.

2. Combined Autocorrelation Method

Many methods for tissue elasticity imaging are based on static tissue compression, which measure the strain distribution inside a body produced by compressing or relaxing a tissue as shown in Fig. 1. Mechanical methods with stepping motors have been used for axial compression of tissue. However, as for simple operation, freehand manipulation of ultrasonic probes is desirable. In a freehand compression, it is necessary to be robust to the non-axial movement of the probe on the surface. It is also necessary to have a large dynamic range of strain for stable measurement that does not depend on a compression speed and quantity. To satisfy these conditions, we developed the combined autocorrelation method (CAM).

The CAM produces elasticity images with high-speed processing and high accuracy, and achieves a wide dynamic range for strain estimation by combining two-step processing.

In tissue elasticity imaging, the tissue deformation between two ultrasonic measurements is very small (the value of the strain is about 1%). Therefore, the RF signals before and after compression can be modeled as

$$\begin{aligned} i_1(t,x) &= A(t,x)e^{-j(\omega_0 t-\theta)} \\ i_2(t,x) &= A(t-\tau, x-u_x)e^{-j[\omega_0(t-\tau)-\theta]} \end{aligned} \quad (1)$$

where $i_1(t,x)$ and $i_2(t,x)$ are the complex RF signals measured before and after deformation, respectively. $A(t,x)$ is the envelop, ω_0 is the transducer's center angular frequency, τ is the time shift, and u_x is the lateral displacement.

First, we obtain the IQ signals (the base-band signals) $s_1(t,x)$ and $s_2(t,x)$ demodulating these RF signals using the quadrature detector, and the complex cross-correlation function between $s_1(t,x)$ and $s_2(t+nT/2, x+mL)$ is defined as

$$\begin{aligned} R_{12}(t,x;n,m) &= \iint_D s_1(t+v, x+w) \\ &\quad \times s_2(t+nT/2+v, x+mL+w)^* \, dvdw \\ (n &= -N_{\min}, \Lambda, -1, 0, 1, \Lambda, N_{\max}) \\ (m &= -M_{\min}, \Lambda, -1, 0, 1, \Lambda, M_{\max}) \end{aligned} \quad (2)$$

where T is the period of the ultrasonic signal, L is the interval of scan lines and D is the correlation window size. Substituting $s_1(t,x)$ and $s_2(t,x)$ expressed by eq. (1) into eq. (2), the correlation function. $R_{12}(t,x;n,m)$ can be given as

$$R_{12}(t,x;n,m) = R_A(t,x;\tau - nT/2, u_x - mL)e^{-j\omega_0(\tau - nT/2)} \quad (3)$$

where $R_A(t,x;\tau,u_x)$ is the autocorrelation function of the envelope.

The first step is coarse estimation by searching maximum envelope correlation. The key feature of this method is to search only on the grid points of the 1/2 wavelength interval in the axial direction and the interval of scan lines in the lateral direction because the purpose is to detect a zone without phase aliasing in a large dynamic range. Thus, an improvement in the processing speed is attained by this method. Here, the 1/2 wavelength interval in the axial direction enables us to optimize computing efficiency without phase aliasing. Moreover the CAM is robust to sideslip and suited to freehand compression by implementing a 2-D search in lateral directions.

The second step is a fine estimation by using the unwrapped phase $\phi(t,x;k,l)$ of R_{12} which is obtained by the first step. The time shift τ, the axial displacement u_y and the lateral displacement u_x at a measurement point (t,x) are given respectively by

$$\left.\begin{aligned} \tau &= -\frac{\phi(t,x;k,l)}{\omega_0} + \frac{kT}{2} \\ u_y &= \frac{c\tau}{2} \\ u_x &= lLR_A \end{aligned}\right\} \quad (4)$$

where c is the ultrasound velocity. Finally, the axial strain distribution can be obtained by differentiating the axial displacement distribution spatially.

We have verified the ability of the CAM through simu-

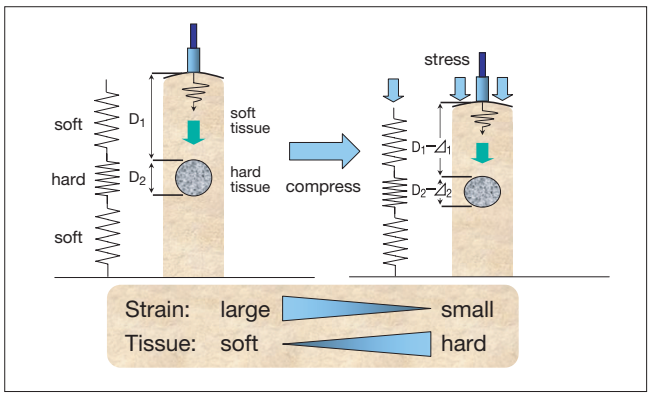

Fig. 1 : ID-spring model of tissue deformation

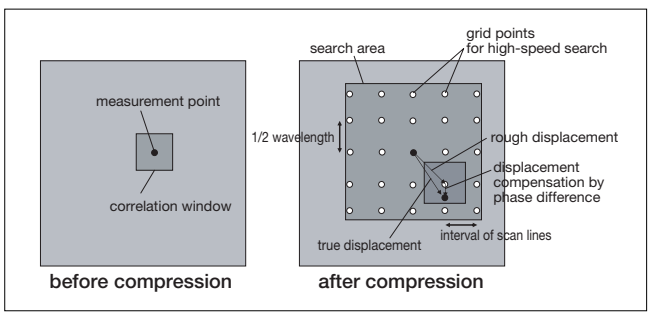

Fig. 2 : Schematic diagram of CAM

lations and phantom experiments. Performance depends on parameters such as window sizes. They are decided from the result of the phantom experiment based on the conditions required for the fine strain image. In this study, we use the 1.2mm (axial) × 1.0mm (lateral) correlation window and the 3.2mm (axial) × 2.2mm (lateral) displacement search area. In this case, it is shown that the processing speed of the CAM is about 7.7 times as fast as that of the conventional spatial correlation method, and the accuracy of the extended CAM is twice as accurate as that of the spatial correlation method[4]. Furthermore, it is shown that the dynamic range of strain estimated by the extended CAM is 0.05% to 5.0% (the optimal dynamic range is 0.5% to 2.0%) and this method can support about 4mm lateral slip[3].

3. Development of Tissue Elasticity Imaging System

We attempted to develop a real-time tissue elasticity imaging system by implementing the CAM algorithm. At first, an experimental system was constituted and their basic performance was evaluated by phantom experiment. Fig. 3 shows an initial result of evaluation of spatial and contrast resolution. In this experiment, a convex probe with a center frequency of 3.75MHz was used. Phantom was gelatin-based cube with Young's modulus of 10kPa which includes sphere with different diameter and Young's modulus. Fig. 3(a) indicates that at least small inclusion

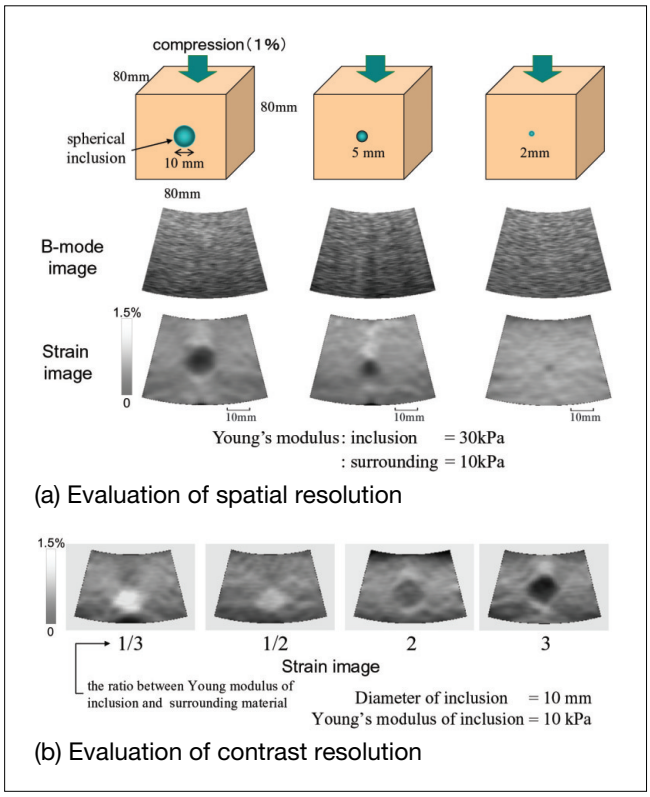

Fig. 3 : A result of phantom experiment for evaluation of spatial and contrast resolution (3.75MHz convex probe)

with a diameter of 2mm and three times harder than surrounding material can be detected in strain image, while it can not be recognized in B-mode image. In terms of contrast resolution, Fig. 3(b) shows that at least twice harder inclusion with a diameter of 10 mm can be clearly depicted. This implies that breast tumor can be detected because according to the report by Krouskop[8], Young's modulus of beast cancer (Invasive ductal carcinoma) is more than three times larger than normal glandula mammaria. The spatial and contrast resolution are related with each other, then they were examined in detail by simulation analysis. Although the performance depends on system parameters such as the center frequency, these results validate the developed method is applicable to practical use.

Next, we stared to integrate the imaging system into a commercial ultrasound scanner in cooperated with HITACHI Medical Corporation from 2001[9]. After a preliminary investigation based on a prototype, by utilizing a significant amount of computation power available in ultrasound scanner (EUB-8500), and developing high-performance programs to implement the CAM algorithm, a real-time tissue elasticity imaging system was released in January, 2004.

The echo signals are captured in real time while the probe slightly compresses or relaxes the body through freehand operation. The small compression plate is usually attached to an ultrasonic probe so that the stable tissue compression is attained and the stress field is transmitted more uniformly; consequently, a good strain image is obtained.

The strain of tissue is color-coded according to its magnitude and translucently superimposed on the conventional 2D images. This simultaneous display enables us to understand anatomical correspondence between tissue elasticity image and the conventional B-mode image. In our color scale strain image, red indicates that tissue is soft and blue that it is hard. In addition, several post-processing techniques such as frame-to-frame smoothing have been implemented. The mean of strain distribution within a ROI is calculated and the display range is adaptively changed using this mean value. As a result, the stable strain image can be obtained without depending on the level of compression.

4. Clinical Assessment and Discussion

The clinical assessment of the system was performed on breast tissue. The upper of Fig. 4 shows a non-invasive ductal carcinoma (age 39, F). In the B-mode image, the tumor with a diameter of about 6 mm may be observed but the boundary is not clear, while in the strain image the tumor is shown as hard region, which coincides with the report that breast cancer generally becomes hard. The bottom of Fig. 4 illustrates a case of fibroadenoma (age 42; F).

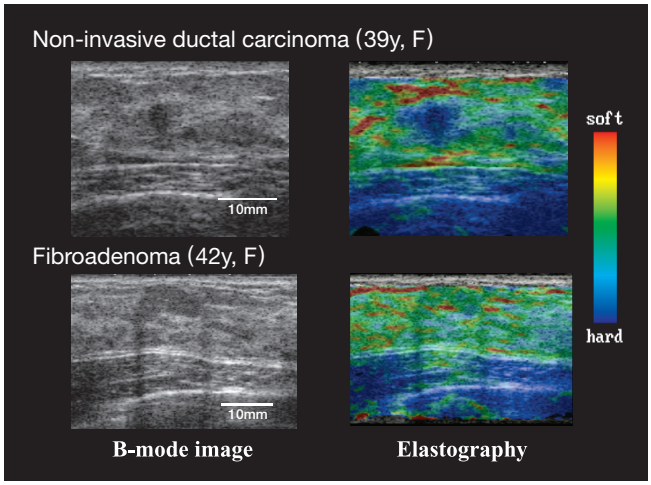

Fig. 4 : Results of breast tumor diagnosis
The upper left is a conventional B-mode image of noninvasive ductal carcinoma. The right is an elasticity (strain) image. The tumor has a diameter of about 6 mm in the figure. The bottom is an fibroadenoma. The color of the tumor area indicates that it is as soft as surrounding tissues.

In this case, the tumor is benign and the color of area of the tumor indicates that it is as soft as surrounding tissues. This corresponds with empirically well-known knowledge acquired through palpation.

Based on the diagnosis of more than 100 cases of breast tumor by tissue elasticity images, Dr. Itoh et al. constituted scores of malignancy, which is referred to as 'Tsukuba elasticity score', by categorizing patterns of elasticity images of breast tumors into five classes from malignancy to benign. As a result of diagnosis based on the elasticity score, it was revealed that even non-expert could attain precise diagnosis of breast cancer based on elasticity score as well as experts since the criterion on elasticity score is much simpler than conventional B-mode images[10].

At present, real-time tissue elasticity imaging is based on the strain which is a relative parameter regarding hardness of a tissue and one dimensional or axial strain. Therefore, it should be noted that the stain represents the tissue deformation and does not always correspond to tissue hardness so that it is difficult to perform a pathological diagnosis only from a strain image. However, the strain image is still considered to be effective in diagnosis since we can acquire the information of the tissue hardness which is not obtained from the other conventional diagnostic equipment. I have no doubt that improvement in diagnosis is expected by using the stain image as complementary to B-mode image. The more quantitative elasticity image based on elastic modulus will be realized before long.

5. Conclusion

We developed a novel technology (CAM) for the tissue elasticity imaging system which enables us to measure the strain in real-time and stably by freehand compression. Practical system based on the CAM was developed with cooperation with Hitachi Medical Corporation. Results of clinical evaluation demonstrated the high quality strain images *in vivo* and high potential of real-time elasticity image for breast examination, especially for the detection of carcinoma.

In order to establish the criterion of diagnosis based on tissue elasticity, we must acquire more clinical data and investigate the relation between tissue elasticity and pathological classification. Recently elasticity imaging is evolving into diagnosis in the wider clinical fields including thyroid and prostate, and treatment-aid tool such as HIFU. In addition, it is expected that in the future technology for tissue elasticity imaging will be more sophisticated such as three dimensional and quantitative elasticity images based on elastic modulus.

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