Breast Tissue Assessments Based on High Order Mechanical Properties

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Summary. Ultrasonic tissue elasticity imaging, which can visualize diseased tissues based on their stiffness, is a useful technique for breast cancer detection. In general, soft tissues including the breast have nonlinear elasticity and viscoelasticity referred to as high order mechanical properties. These properties make the conventional elasticity evaluations based on strain and Young's modulus images difficult because these images vary depending on various conditions, in which high order mechanical properties cannot be neglected. For mechanical assessment independent of such conditions, high order mechanical properties must be assessed. Moreover, these properties also change in diseased tissues. Therefore, in this chapter, a method to assess high order mechanical properties is proposed with the aim of improvement of diagnostic ability. In actual breast assessment, cyclic loading and unloading were applied to the body surface by freehand manipulation of an ultrasonic probe; then, the nonlinear elasticity and viscoelastic hysteresis parameters were estimated and visualized based on the surface pressure measured with the pressure sensor, and the local strain distribution was estimated by the combined autocorrelation method. Nonlinear elasticity and hysteresis parameters, which can be estimated by the proposed method, clearly discriminated the breast tumor from the surrounding normal tissue.

Key words. Strain, Nonlinear elasticity, Hysteresis, High order, Breast tissue assessment

Introduction

Ultrasonic tissue elasticity imaging, which can visualize the diseased tissues based on their stiffness, is a useful technique for breast cancer detection because the cancer is generally harder than normal tissue. Conventional elasticity imaging is mainly based on the primary elastic properties such as strain and Young's modulus under small

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deformation, in which linear elasticity assumption is valid. In general, soft tissues including the breast have nonlinear elasticity and viscoelasticity [1], which are referred to as high order mechanical properties in this chapter. High order mechanical properties make the conventional elasticity evaluations difficult because these image patterns vary depending on the magnitude and speed of compression, in which high order mechanical properties cannot be neglected. For mechanical assessment independently of these conditions, high order mechanical properties must be assessed. Moreover, these properties also change in diseased tissues. Therefore, the assessments of high order mechanical properties are prospective for improvement of diagnostic ability.

In this chapter, high order mechanical parameters to characterize the nonlinear elasticity and the hysteresis in viscoelastic property are introduced, and a method to estimate these parameters is proposed. The potential of this method was investigated through in vivo measurement of breast tissue.

A Method to Estimate High Order Mechanical Prameters

Figure 1 shows a typical uniaxial stress–strain relationship of soft tissue in the loading and unloading processes within a certain time period. Each curve is nonlinear, and both processes produce a hysteresis loop due to viscoelasticity. In the biomechanics field, it is well known that the stress–strain relationship of soft tissue exhibits an exponential character. From this empirical information, the stress–strain curve in the loading process is approximated by including an exponential function as follows [2]:

$$\sigma = (A/B)\{\exp(B \cdot \varepsilon) - 1\} \tag{1}$$

where σ and ε are the axial stress and strain, and A is the Young's modulus when the small deformation is applied; B is the nonlinear elasticity parameter defined in this chapter and can express the intensity of nonlinearity. By fitting the measured values of stress and strain to Eq. 1, B can be extracted.

On the other hand, the hysteresis parameter to characterize the hysteresis property in viscoelasticity can be defined based on the area of hysteresis loop H as shown in Fig. 1. Because the area of hysteresis loop depends on the turning strain ε_0 between the loading and unloading, this index should be normalized by the strain energy function S_l in the loading process as follows [3]:

$$R = H/S_l \tag{2}$$

where R is the hysteresis parameter defined here and takes values from zero to 100%. Therefore, R can evaluate the hysteretic property quantitatively.

Not only Young's modulus, but also high order mechanical parameters B and R vary depending on tissue component and degeneration. Moreover, B is constant independently of the compression magnitude if the exponential formulation is valid, and R is also close to constant independently of the compression speed because the hysteretic property is almost constant to the varying deformation rate [1]. Therefore, high order mechanical parameters have potential to provide useful diagnostic information

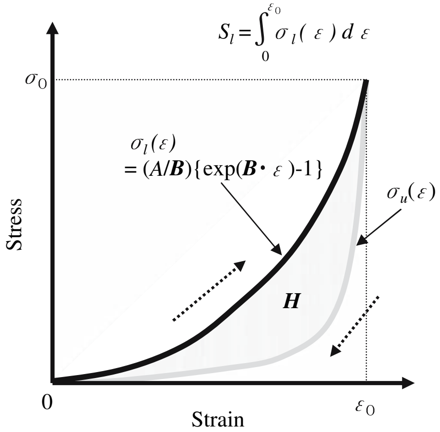

FIG. 1. Typical uniaxial stress–strain relationship of soft tissue in the loading and unloading processes during a certain time period

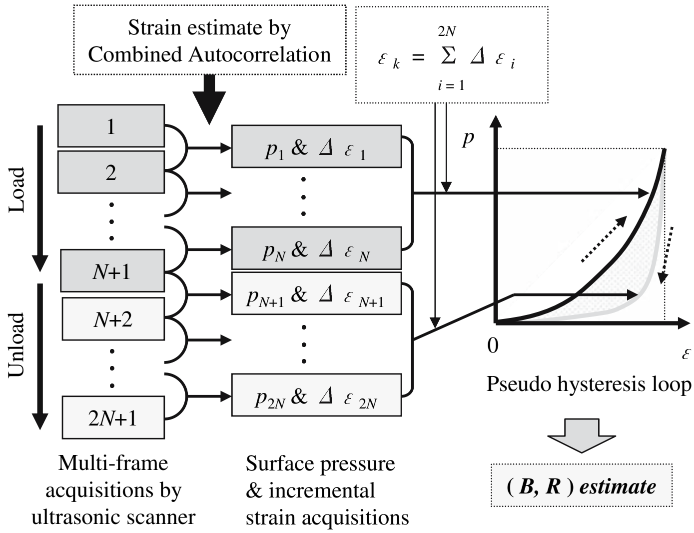

FIG. 2. A method to estimate the distribution of high order mechanical parameters

for improvement of diagnostic ability independently of the magnitude and speed of compression.

Figure 2 shows a method to estimate the distributions of high order mechanical parameters. To achieve this, local stress–strain curves are required. First, in parallel with cyclic loading and unloading applied to the body surface at constant speed, multiple rf frames are acquired with the ultrasonic scanner. Between the adjacent frames, incremental strain $\Delta\varepsilon_k$ ($k = 1, 2, \ldots, N, N + 1, \ldots, 2N$) distributions are estimated by differentiating the axial component of a two-dimensional displacement vector obtained based on the combined autocorrelation method [4]. Strains ε_k, which correspond to the horizontal axis in the local stress–strain curves, are calculated by accumulating the traced incremental strain based on the two-dimensional displacement vector. At the same time as multiple rf frame acquisitions, time-series surface pressures p_k are acquired with the pressure sensor for obtaining the stresses, which correspond to the vertical axis in the local stress–strain curves. However, stress estimation is one of the most difficult problems in the elasticity imaging. In this chapter, instead of the internal stress estimation, the measured value of surface pressure is used for obtaining the pseudo stress–strain curves as a trial. Once the pseudo stress–strain curves are obtained, the nonlinear elasticity and the hysteresis parameters can be locally estimated by the aforementioned procedures. The usefulness of this method has been investigated by preliminary experiments for the porcine femur and kidney [2, 3].

In Vivo Experiment of Breast Tissue

An in vivo experiment of breast tissue that had suffered from fibroadenoma was performed. Cyclic loading and unloading forces to the body surface were applied by freehand manipulation of an ultrasonic linear array probe (Hitachi; 7.5 MHz) for about 2 s. A small acrylic compressor was fixed to the probe, and a pressure sensor was embedded in the compressor near the probe for surface pressure measurement.

Figure 3a,b shows the B-mode and the conventional strain images of the fibroadenoma obtained at the initial stage in the loading process. Although the fibroadenoma is unclear in the B-mode image, the strain image displays the fibroadenoma as a low strain area. On the other hand, Fig. 3c,d shows the nonlinear elasticity and the hysteresis parameter images. The nonlinear elasticity parameter image provides a high-contrast image and clearly displays the fibroadenoma as a high nonlinearity area. The hysteresis parameter image can also visualize the fibroadenoma as a low hysteresis area. Although the high order mechanical parameter images substantially seem to reflect the morphological structure of the breast as shown in the B-mode image, they depict different patterns from the conventional B-mode and strain images. Therefore, high order mechanical parameters might also provide useful information for breast tissue diagnosis independently of the conventional images such as B-mode and strain.

Conclusions

With the aim of improvement of diagnostic ability and mechanical assessment independently of the magnitude and speed of compression, a method to estimate the high order mechanical parameters was proposed in this chapter. As understood in the experimental results, high order mechanical parameters might provide useful information that differs from the conventional images such as B-mode and strain. These parameters can be chosen according to any case in the clinical diagnosis. To clarify the meaning of high order mechanical parameters, the relationship between these parameters and the pathology should be investigated in the future.

Moreover, in this work, because the internal stress distribution is not obtained, the estimated high order mechanical parameters are not quantitative. For quantitative

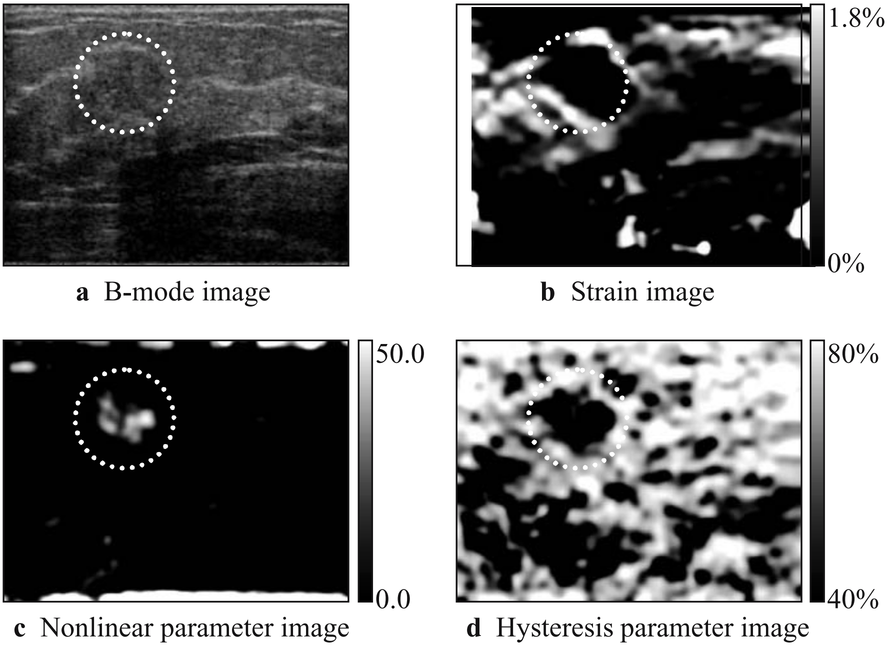

FIG. 3. In vivo experimental results with breast tissue that suffered a fibroadenoma. **a** B-mode image at initial stage in the loading process. **b** Strain image at initial stage in the loading process. **c** Nonlinear elasticity parameter image. **d** Hysteresis parameter image. *Open circle with dotted line* on each image indicates the region of fibroadenoma

estimations, the internal stress distributions should be estimated, or the influence of them should be eliminated. In future research, we intend to resolve these problems.

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