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Optimal Frequency for Vibrational Optical Coherence Elastography (OCE) on Tissue Mechanical Properties Characterization

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ABSTRACT

Pathological change tends to alter tissue mechanical properties, e.g. tissue stiffness. Current elastography technology use tissue stiffness as a signature to diagnose and localize diseases. Our team focus on vibrational optical coherence elastography (OCE) for its capability to increase signal to noise ratio as well as its high resolution comparing other elastography modalities. The result highly relies on the stimulation frequency for vibrational mode might change as frequency varies. A proper frequency range is required however, there hasn't been a consensus among the research groups. In order to find the proper frequencies, several parameters measured from real experiment are input in transient model of ANSYS to simulate vibrational pattern of the sample with driving frequencies vary from 100Hz to 1000Hz. An upper limit of frequency has been discovered finally.

Keywords: vibration; stimulation frequency; optical coherence elastography; mechanical property

1 INTRODUCTION

Stiffness change in human tissue is linked with its pathological conditions. For example, clinicians will conduct a digital rectal exam to patients by feeling the prostate with finger through rectum, a hard or lumpy region is usually considered as a sign of cancer [1]. Thus, stiffness measurement is a promising guide to aid diagnosis and localisation of lesions. Ultrasound elastography and MRI elastography have proved the investigation change of tissue elasticity can yield several pathology information which can aid further treatments [2, 3]. Prognosis is vital for patients' survival as a medical care for skin cancer at an early stage will increase the 5-year survival rate and the chance of cure [4]. But there is one inevitable drawback of ultrasound elastography and MRI elastography that resolution is not fine enough to accurately delineate boundary of lesion, thus optical coherence elastography is utilized to handle this problem with a resolution in micro-meter scale.

Vibrational optical coherence elastography (OCE) is an imaging tool to reveal stiffness internal sample. The theoretical base of OCE is phase sensitive optical coherence tomography (PhS-OCT), a volumetric label free imaging modality with the capability to detect deformation even in nanometre scale. A sinusoidal vibration is administrated to the scanned sample where its deformation varying with time is detected and recorded by PhS-OCT, as stiffer region tends to have a smaller strain with the presumption that stress field is evenly distributed, relative stiffness can be mapped out by analysing as well as calculation of the deformation data.

Vibrational OCE has several advantages when compared with other elastography imaging. It is a label free, non-invasive technique with higher resolution than ultrasound elastography and MIR elastography. It also has the capability to characterize microscale morphology and mechanics of soft tissue which holds promise for future clinical diagnose. Among all the OCE methods, vibrational OCE inherits high resolution of OCT system with an axial and lateral resolution both in micrometre scale, which is better than those of shear-wave OCE with a decreased lateral resolution for its algorithm [5]. The SNR of vibration is also higher in vibrational OCE for its algorithm by analysing hundreds of frames at one time [6].

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Presumptions has been proposed for vibrational OCE that stress field is evenly distributed in sample which indicates that stress is uniaxial and is uniform along the depth, this can be realized by a uniform compression with a couple of flat surfaces parallel to each other which confine the sample in between. Tissue assessed by OCE is reckoned linear elastic, it accords to the nature that soft tissue holds within a strain up to 10% [7], this required a proper applied strain ensuring deformation is in the elastic region, relationship between elastic modulus and strain can be represented as:

$$E = \frac{\sigma}{\varepsilon}$$

To meet the requirements from presumptions, several parameters must to be settled such as stimulation frequency. A high frequency compression load might lead to concentrated stress which violates the presumption of evenly distributed stress field, on the other hand, a uniform stress field is ensured when low frequency vibration is administrated, but viscous effect will lead to a non-linear stress-strain behaviour which can blur the final elastic mapping. Several frequency bands have been utilized by our research peers, Brendan F. Kennedy et.cl selected 850 Hz for excitation frequency to reduce viscosity in 2009 [8], a frequency range of 20 Hz to 350 Hz was chosen for stimulation by Xiang Liang et.cl [9], a year later their team set the compression frequency from 50 Hz to 250 Hz [10], Shaghayegh Es'haghian et.cl used a step-wise stimulation with a frequency of 14Hz, No consensus has been reached for the optimal frequency employed for vibrational OCE.

This paper illustrates the optimal frequency by simulation with harmonic model constructed in ANSYS. We use harmonic model of ANSYS to simulate real practice we used in experiment with a frequency range between 100 Hz and 1000Hz. Results of deformation at different frequencies are further analysed and evaluated with mathematical tools. A proper frequency range is proposed in the final of paper.

2 METHODS

2.1 Model Selection of ANSYS Simulation

A harmonic model in ANSYS 14.5 is utilized to simulate response of a linear structure to applied sinusoidal loading at steady state. It can serve as a tool to investigate whether the material is able to resist fatigue and other harmful effects towards cyclic loading [11]. Results of simulation only accounts for steady-state vibration, whereas transient response at beginning of loading is excluded.

Vibrational OCE only acquires steady-state vibrational data which is suitable to use harmonic model to explore cyclic stress-strain filed internal sample. Human tissue is considered as linear elastic under vibrational OCE, which also meets the description of ANSYS document where nonlinearities are ignored in simulation. Thus, harmonic model is suitable for simulation vibration applied in OCE.

2.2 Engineering Data

Material selected for simulation is 2% agar-agar phantom with a measured elasticity of 193 kPa by surface acoustic wave OCE in our lab [12]. Its stiffness lies in the elasticity range of epidermis varying from 88 to 300 kPa [11], whose harmonic response can be utilized as a reference to the scenario of real human skin. Viscoelasticity of 2% agar phantom can be analysed by stress-relaxation test, however time varying stress and strain data highly depends on several parameters of testing, such as speed of load and magnitude of strain. And most importantly, stress-strain behaviour in relaxation test possess a longer time scale when compared with vibration in hundred Hz thus general test methods for measurement of viscoelasticity behaviour of 2% agar are inaccessible [13]. Dynamic test is also available to test mechanical property of agar however there's near lack of scheme to investigate stress-strain distribution in sample when different cyclic frequencies are provided. Due to these complications, viscosity is not included in ANSYS simulation. Density of agar phantom is set 1000 kg/m^3 which is close to water as the phantom is mainly composed of water and its volume doesn't shrink in cooling process. Poisson ratio is set to 0.4 referred from publication by Anand and Scanlon, 2002 [14].

2.3 Model Configuration

Geometry of sample configured in ANSYS has a cubic shape with equal edge length of 5mm and meshing size is set as 0.1 mm to minimize the number of meshing elements and to reduce time required for computation. Other parameters are remains default for mesh in ANSYS 14.5 workbench. Sinusoidal formation is administrated from bottom plane of sample with a static amplitude of 1000 nm, suppression is not added to bottom plane. Top surface is fixed to simulate practical scenario where the top surface of sample is fixed by the lower plane of glass window, illustrated as blue surface in Figure 1a.

Frequency in analysis settings varies from 100 Hz to 1000 Hz with an equal interval of 100 Hz, which is shown as the yellow arrow in Figure 1a, solution method is set to be full. Deformation probes are attached in mid plane at the meshing points, shown in Figure 1b, only deformation in axial direction is taken into consideration, this accord with current OCT system with the capability to detect deformation only in axial direction. There are two reasons to choose the mid line for probes to attach, first this is the area where practical experiment interested in, second this volume is far from boundary which indicates the boundary condition is trivial at this location, results are highly relies on vibration itself.

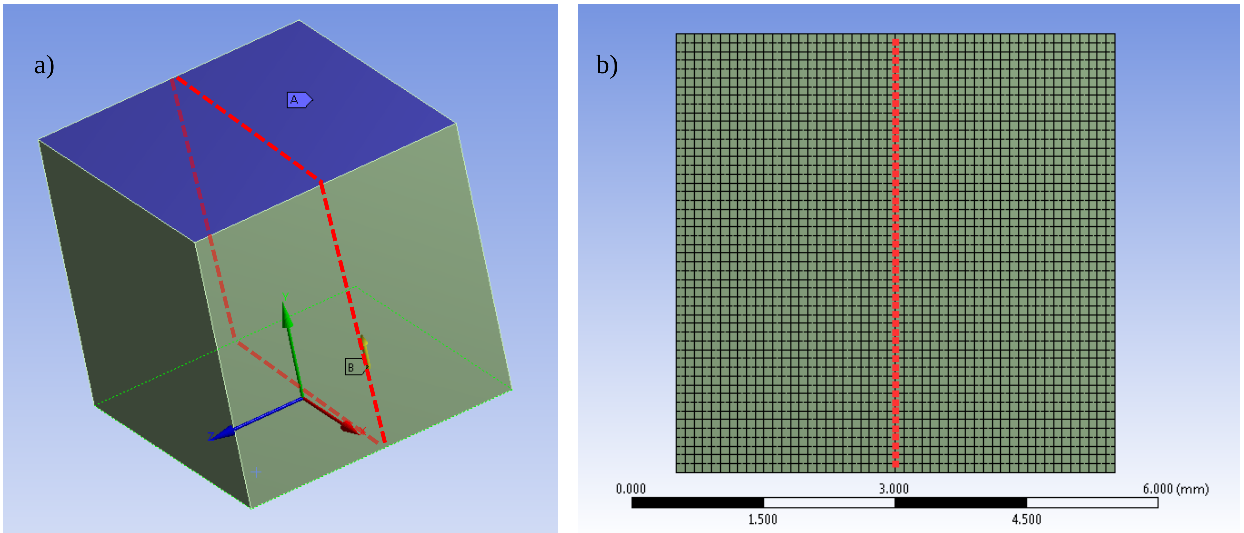

Figure 1 a)Fixed top surface (blue signed as A) and applied sinusoidal loading (yellow arrow) from bottom surface. The Y-axis shown in green represents the positive axial direction. b) The deformation probes attached in the mid plane, which is shown as dashed line in figure a.

3 RESULTS DISCUSSION & CONCLUSION

An optimal frequency is considered to have an evenly distributed stress filed indicating that an alteration of strain can be utilized as signature to reveal stiffness change. An evenly distributed strain is expected for the optimal frequency, in other words, the axial deformation amplitude should be linear to depth, R^2 of linear fitting for depth-deformation curve is a vital parameter to evaluate the performance of vibrational OCE at certain frequency, it represents degree of linearity where a larger R^2 indicates a better linearity of deformation profile and a more evenly distributed stress field.

To evaluate simulation results with method mentioned above, deformation profile collected from inserted probes is retrieved and plotted, shown in Figure 2 where the x-axis represents depth, defined as the distance to the top fixed surface, the y-axis is the sinusoidal deformation amplitude. As an intuition, linearity between depth and vibration amplitude drops as frequency increases, this accords to the common view that concentrated stress and strain field might appear when frequencies are too high, which contributes to loss of linearity. To quantify the loss other than intuition, linear model is applied to simulated results

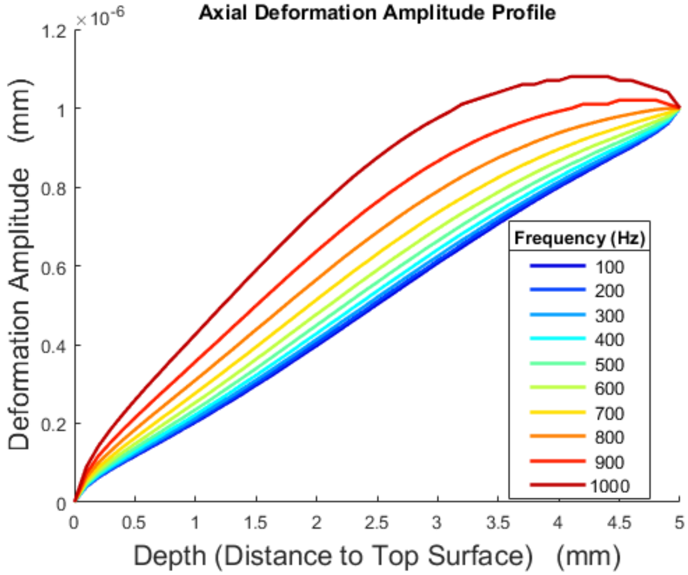

Figure 2 Axial deformation amplitude profile. Data plotted in this figure are retrieved from deformation probes, shown in Figure 1b.

in MATLAB, mind that deformation amplitude inside 0.1 mm are not consistently linear compared with the remaining profile. This can be traced back to confounders near boundary, thus this depth range near window glass is out of interest in the following analysis. R^2 is acquired to evaluate degree of linearity, which is shown in Figure 4, it gradually drops from nearly 1 at 100 Hz to 0.946 at 1000 Hz. The drop is result of concentrated stress filed which gradually becomes evident as frequency increases.

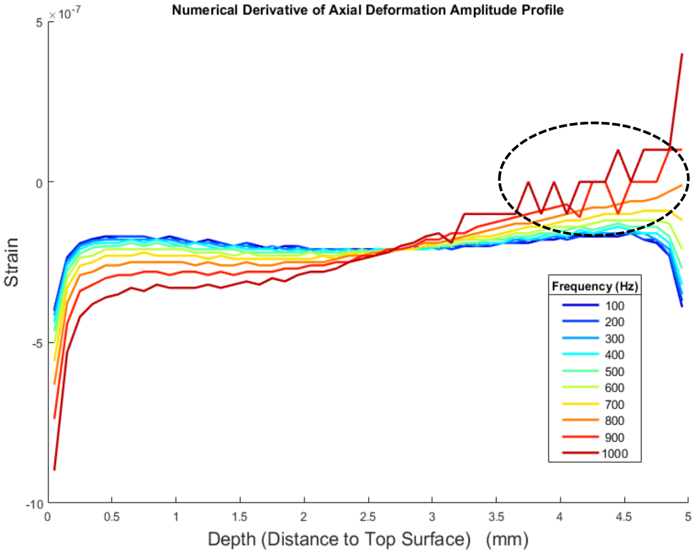

Figure 3 1st derivative of deformation amplitude (Figure 1a). The dashed circle emphasizes the existence of concentrated strain field resulted from concentrated stress field.

As illustrated in Figure 2 the red curve to the top of 1000 Hz, its deformation amplitudes from 4 to 4.5 mm are even larger than that of 5mm where external deformation is applied, representing the existence of concentrated stress. To have a better vision of concentrated field, a first derivative is administrated to deformation amplitude data to acquire axial local strain, shown in Figure 3, where prominent peaks are observed at frequency 900 Hz and 1000 Hz, emphasized in dashed line circle, as the assigned material in ANSYS is homogeneous, a huge variation in strain field indicates a stress filed fluctuation in axial direction. As frequency increases from 100Hz to 1000Hz, strain along the depth becomes less consistent, also reflecting a trend towards stress filed inconsistency.

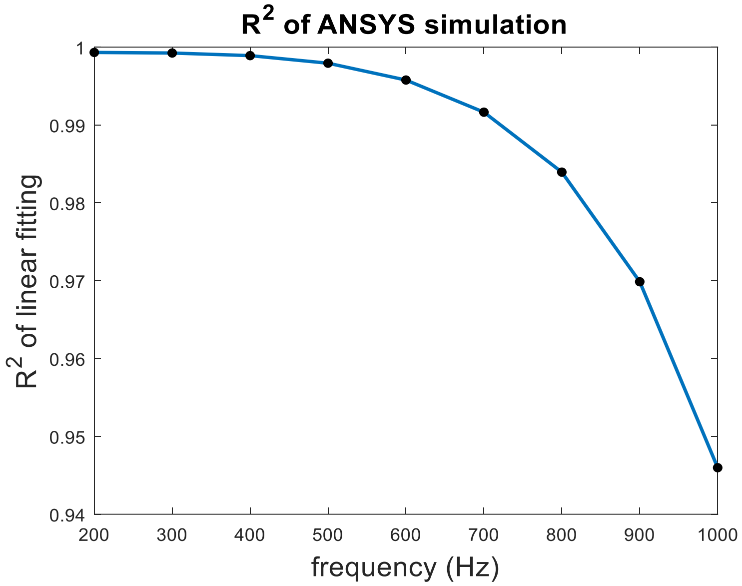

Figure 4 R^2 *to frequency curve.* R^2 *is generated from linear fitting of vibration amplitude to depth curve.* R^2 *drops as frequency increases.*

A proper driving frequency for vibrational OCE ensures an evenly distributed stress field and the sensitivity for stiffness is also enhanced under this scenario. An upper limit of driving frequency processed from simulation data for vibrational OCE is 800Hz, above which there will be a high possibility to generate concentrated stress filed. Viscosity is ignored from simulation but materials like human tissue and agar phantom will inevitably have viscosity behaviour when cyclic loading is applied. There are also some elements omitted from simulation such as friction between surfaces, but these parameters are not accessible for a certain value, and it also highly depends on the material as well as the given boundary conditions. Deformation profile will be different from simulation especially for low frequency regions where viscous effect plays a significant role, thus the lower limit for frequency range cannot be settled. To settle a lower frequency and validate simulation results, practical experiment must be carried out in the future with the same conditions defined in ANSYS, the same evaluation methods are going to be implemented on data collected with practical experiment.

Thus, the upper limit of vibrational OCE is 800Hz, frequencies above 800 Hz are not recommended to conduct the experiment.

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