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Abstract

Estimation of heat generation is important for use of an ultrasonic surgical knife to suppress undesirable damage to the normal tissue. For this purpose, it is better to measure viscoelastic constants of tissue prior to application of a knife. In this study, using a network analyzer, viscoelastic constants were estimated by measuring admittance characteristics of the knife with and without being contacted with an object. Measured resistance \(r\) and capacitance \(C\) of the equivalent electric circuit correspond to elastic modulus \(G\) and inverse of viscosity coefficient \(\eta\) of the object, respectively. The estimated elastic modulus of chicken muscle (98 kPa) was in good agreement with that reported in literature (100 kPa).

1. Introduction

In this study, we investigated the ultrasonic surgical knife which is one of the medical treatment technologies with ultrasound. The ultrasonic surgical knife can cut soft tissues using ultrasound vibrations and it can cut a soft tissue and stop bleeding by coagulation at the same time. The ultrasonic knife can coagulate proteins at a comparatively low temperature compared with other surgical knives such as the laser surgical knives, and it is a great advantage to prevent the undesirable injury to the patient together with the effect of stopping bleeding. The improvement of patients’ QOL (Quality of Life) is becoming more and more important in recent years [1][2] However, effects of the ultrasound vibration of the blade on the soft tissue have not been revealed thoroughly so far. The detailed investigation on the influence of the vibration of the tip of the blade would be useful for the improvement of safety and the optimization of efficiency of the ultrasonic surgical knife.

2. Principle

The biological tissue is a viscoelastic body, and a mechanical model (Fig. 1(a)) is assumed as a model of the soft tissue in this report. When an ultrasonic knife is driven by a simple harmonic signal, the stress \(\sigma\) becomes a simple harmonic. In this case the stress-strain relationship shows a hysteresis property as shown in Fig. 1(b) because there is phase delay \(\theta\) of strain \(\gamma\) from stress \(\sigma\). Stress \(\sigma\) and strain \(\gamma\) expressed by the Voigt model are expressed as follows:

\[
\sigma = m \frac{d^2 \gamma}{dt^2} + G \gamma + \eta \frac{d \gamma}{dt},
\]

where \(m\), \(G\) and \(\eta\) are the equivalent mass, static elastic modulus and viscosity coefficient, respectively. The area enclosed with the hysteresis curve which corresponds to the calorific value during a soft tissue being vibrated with an ultrasonic surgical knife. Therefore, when elastic modulus \(G\) and viscosity constant \(\eta\) are estimated, the calorific value and change in the stress-stress relationship by temperature increase can be estimated prior to application of the ultrasonic knife by contacting it with soft tissue.

Fig. 1. (a) Mechanical model. (b) Stress-Strain relationship.

3. Method

In this study, elastic modulus \(G\) and viscosity coefficient \(\eta\) of an object were estimated by considering the equivalent circuit of an object and an ultrasonic knife. Stress \(\sigma\) and strain rate \(\dot{\gamma}\) \((=d\gamma/dt)\) correspond to the voltage and electric current in the corresponding electric circuit, respectively. Admittance characteristics \(Y(\omega)\) of the knife with and without being contacted with the object were measured with a network analyzer (HP8751A). Equivalent mass, elastic modulus \(G\) and viscosity coefficient \(\eta\) correspond to the measured inductance \(L\), inverse of capacitance \(C\) and resistance \(r\) of the equivalent circuit of the object, respectively. The experiments were conducted for silicone rubber (48.8 kPa) and a soft tissue (a chicken breast muscle).
4. Results

Admittance characteristics $Y(\omega)$ of the ultrasonic knife without load, loaded by soft tissue, and loaded by silicone rubber were measured as shown in Figs. 3(a) and 3(b). The changes in resonance frequency $f_0$ and the size of the radius of the admittance circle were measured. Resistance $\hat{R}_a$, capacitance $\hat{C}_a$, and inductance $\hat{L}_a$ of the soft tissue and silicone were determined by comparing the admittance of the equivalent circuit without load with that with load [3].

Resistance $\hat{R}_a$ and capacitance $\hat{C}_a$ of the soft tissue were estimated to be 15.4 $\Omega$ and 1.77 nF, respectively, and those of resistance $\hat{R}_a$ and capacitance $\hat{C}_a$ of the silicone rubber were 20.4 $\Omega$ and 3.75 nF, respectively. The capacitance of the soft tissue was about twice larger than that of silicone rubber. Therefore elastic modulus $G$ of the soft tissue was estimated to be 98 kPa by referring to elastic modulus $G$ of silicone rubber (48.8 kPa) because the inverse of capacitance correspond to the elastic modulus. The estimated elastic modulus of soft tissue (98 kPa) was in good agreement with that reported in literature (100 kPa [4]).

The inverse of capacitance and resistance of soft tissue when the end of the tip contacted with the tissue was nearly triple larger than those when the side of the tip contacted. When the end of the tip contacted, the tip included the normal strain in the tissue. Such deformation is dependent on complex Young’s modulus $E + j\lambda$. On the other hand, the shear strain induced by the contact of side of the tip with the tissue was dependent on the complex shear modulus $G + j\eta$. When a material is incompressible, $E = 3G$ and $\lambda = 3\eta$ [5]. The experimental results showed these relationships because a soft tissue is almost incompressible.

5. Conclusion

In this report, the equivalent electricity resistance, inductance and capacitance of the soft tissue were measured with a network analyzer. It will be possible to assess the calorific value in the application of an ultrasonic knife by enabling the estimation of viscosity coefficient $\eta$ by further investigations.

Fig. 2. Experimental set up (a) End of tip contact. (b) Side of tip contact.

Fig. 3. (a) Admittance $Y(\omega)$ and. (b) Admittance circle when the end of tip contacted. (c) Admittance circles of chicken muscle when the end and side of the tip contacted.

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References