A SIMULATION METHOD FOR 3-DIMENSION NEEDLE INVASIVE MEDICAL TREATMENTS OF CANCER INFECTED LIVER

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ABSTRACT
The medical insertion treatments on cancer infected liver seem to be very effective because of low invasion for patients. Planning for insertion procedure is difficult because the interaction between needle and soft tissue become complicated and the liver may deform largely under the influence of such gravity, cancer, position of needle and so on. It is of significant to grasp natural properties and deformations of liver during medical needle insertion. In this study, viscoelastic material properties are measured by experiments and constitutive equation is formulated based on the experimental results. Then a liver is modeled by finite elements made from the sliced MRI images. 3-Dimensional needle insertion procedures are simulated by quasi-static analysis assuming friction between the needle and soft tissue and conditions of tear-off elements. From the numerical results by the proposed simulation method, it is found that some navigation of the needle insertion is necessary to hit the cancer correctly.

KEY WORDS
Viscoelasticity, liver modeling, strain energy, needle insertion

1. Introduction

Simulator development for medical training purpose has induced a need for a new study on material evaluation of human organs such as liver. There are many works reported on liver modeling and simulation\[1\][3][3]. Liver of human organs is of interested for its time-dependency due to viscoelastic property and experience large elastic deformation. Beside property of liver itself, liver is surrounded by lots of blood vessels and this heterogeneous, nonlinear viscoelastic behaviour of soft tissue is difficult to characterize.

Typically, force-displacement responses of in vivo soft tissues are often attained and being studied. There are various methods to acquire force-displacement data such as tensile test, compress test and also shear stress test \[1\][2][3]. However, none of them stated the most suitable test for this kind of tissue, shows the difficulties of it. An approximation using hypoelastic and rubber-like method such as Arruda-Boyce, Ogden etc. also become the popular methods\[4][12]. Significantly, even the method has high accuracies at high degree of functions; one could not estimate the behaviour of large deformation beyond measured quantities.

Minimal invasive surgery produces a fast recovery and less damage to the patient. Lately surgical treatments of cancers in liver are often carried out making use of needle insertion, then there is tendency to model insertion simulation considering the needle deflection \[5\]~\[10\]. However, it is difficult to steer needle once it is inserted through the liver, unless it is designed to, and this would induce a need to design high performance of surgical robot. In simulation, a simple relatively rigid needle model is used with consideration to the tip geometry and force modeling are studied \[5\]~\[8\]. Simulation in earlier paper stated a 2-dimensional work, and also 3-dimensional work, which most of them only studied about liver deformation itself. A simple fracture mechanics approach to model energy relation shows that friction forces play an important role. In addition, the type of needle tips also affected in smoothing the cutting process. Beside a dynamic approach, a quasi-static approach seems to be more popular and accurate in estimating the forces needed by the needle to insert to in vivo model.

2. Liver Modeling

Liver of human organs has a viscoelastic properties and time-dependence materials. Unlike plasticity, no energy is lost and the process is conservative. Load and unload process of this material are on the same curve, so that no permanent inelastic strains are induced. All materials
exhibit viscoelastic response; elasticity or spring-like behaviour does not exist in real materials but is an approximate description of materials for which the viscoelastic effects are small enough to ignore. In this section, we proposed a rubber like approach to evaluate large deformation behaviour of liver and needle insertion simulation.

2.1 Finite Element Model

To create a 3D finite element (3D FEM) model of human liver, we used for about 150-200 pieces of MRI images of liver of an adult 30-years old man, that were then laminated together to prescribe coordinates about their outer shape. These coordinate data are then converted to CAD file (STL), so that we can make surface model. We then used auto meshing process to gain 3D solid element model. We then gained a model of 7288 elements (Fig.2.1), which was smoothly worked for every simulation mode.

![7288 Elements, 1721 nodes](image)

Fig.2.1 FEM Model of Liver

2.2 Material Properties

A set of creep test was done on pig’s liver using rheometer [1]. Shear strain on test pieces of 10 mm in diameter and 2 ~ 3 mm in thickness were measured. This creep result is used to construct a constitutive relation of stress-strain of liver for all arbitrary time

\[
\tau = \frac{2}{\pi R^3} M
\]

\[
\gamma = \frac{R\theta}{D}
\]

Where, \(\tau\) is shear stress, and \(\gamma\) refer to shear strain.

![Fig.2.2 Outline of Rheometer](image)

Creep test was also done at different stress levels where time intervals for measurement are equalized for each stress. The result shown in Fig.2.3 is the strain for \(t=180\) s. Each strain was the effect of step stress at 20, 50, 100, 200, 300, 500, and 700 Pa. Each test pieces were measured continuously with repetition on relaxation and creep.

![Fig.2.3 Creep Test Result at Different Stress Level](image)

According to nonlinear superposition, creep experiments at progressively higher stress levels, can be expressed as below.

\[
\varepsilon(t) = \int_0^t J(t - \tau, \sigma(\tau)) \frac{d\sigma}{d\tau} d\tau \quad (1)
\]

For step stress history containing a constant load rate segment as in Fig.2.4, step stress can be partially expressed as below.

\[
\sigma(t) = \begin{cases} 
0 & \text{for } t < 0, \\
\sigma_0 \frac{t}{t_r} & \text{for } 0 < t < t_r, \\
\sigma_0 & \text{for } t > t_r 
\end{cases} 
\]

![Fig.2.4 Step Stress Input](image)

By substituting in the Boltzmann superposition integral in Eq.(1),

\[
\varepsilon(t) = \int_0^t J(t - \tau) \frac{d\sigma}{d\tau} d\tau = \int_0^{t_r} J(t - \tau) \frac{d\sigma_0}{d\tau} d\tau \quad (3)
\]

By the theorem of the mean,

\[
\varepsilon(t) = \frac{\sigma_0}{t_r} J(t - t_r, \eta) = \sigma_0 J(t - t_r, \eta) 
\]

in which \(0 \leq \eta \leq 1\). In the experiment, it is well observed that \(t >> t_r\), so that we can express Eq. (4) as below.
In all experiments, the time $t \geq 10t_r$ and is considered sufficient so that errors are not excessive. Observation on results of creep shows that it can be expressed as follows.

$$\varepsilon(t) \approx \sigma_0 J(t)$$

(5)

By substituting Eq.(5) into Eq.(6), creep compliance has the relation as follows.

$$J(t) = \frac{\varepsilon_0}{\sigma_0} t^k$$

(6)

and by the relation between stress relaxation and creep compliance,

$$G(t) = \frac{1}{J(t)}$$

(7)

Constitutive equation of stress-strain relation is expressed as Eq.(9).

$$\sigma = \varepsilon t^k G(t)$$

(9)

With Eq.(9), we can produce a plot of stress-strain relation. However, to predict behaviour beyond measured quantities, we used Mooney-Rivlin Strain Energy Function Method of large elastic material, usually used in analysis of rubber like material. Generalized Mooney-Rivlin Energy Function is stated as below.

$$W = \sum_{r=1}^{R} \sum_{t=1}^{T} C_{rr} (I_1 - 3)^r (I_2 - 3)^t$$

(10)

Then, Eq.(10) is simplified to 3 terms (third order deviatoric function) of Mooney-Rivlin popular energy function.

$$W_{dev}^{frc} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_2 - 3)^2$$

$$+ C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$$

(11)

The reason to use 3 terms function is to avoid unnatural deformations during the act of large external forces.

Here, $C_{10}, C_{01}, C_{11}, C_{20}, C_{30}$ : Material constants obtained from experiment.

$I_1 : \lambda_1^2 + \lambda_2^2 + \lambda_3^2$

$I_2 : \lambda_1^2 + \lambda_2^2 + \lambda_3^2$

show the elongation of materials.

In this simulation, to simplify analysis work, we consider the liver as an isotropic material, although in real world the existences of blood vessels make it in turn should be considered as an anisotropic material.

From Eq. (9) and Eq. (11) of Mooney-Rivlin method, we get following material constants and Fig.2.5 shows that Mooney-Rivlin equation fits experiment data very well.

$$C_{10} = C_{01} = 0.000108507$$

$$C_{11} = C_{20} = -8.79908 \times 10^{-5}$$

$$C_{30} = 0.000906714$$

(12)

This data is then applied to FEM model liver properties using MSC.Marc 2005. Relaxation energy of viscoelastic proper ties is applied using result of creep experiment. As the objective of this paper to simulate cutting behaviour and gaining data for surgery training purpose development, the highest stress value applied during the experiment is used to evaluate liver’s material properties. Energy relaxation at 700 Pa of stress is shown in Fig.2.6 as below.

The other material properties such as friction and density are using the assumed data. For friction, the relative displacement of both liver and needle are obeying the stick slip conditions. We adopted a bilinear coulomb friction force model. In this simulation, only quasi-static approach is considered, so that only displacement of friction force model value is used. As liver sink in the
water, we set a value that for density of liver is larger than density of water.

Table 2.1 Other Properties

<table>
<thead>
<tr>
<th>Variables</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Coefficient</td>
<td>0.1 (Coulomb bilinear)</td>
</tr>
<tr>
<td>Liver Density</td>
<td>$1.0 \times 10^{-5}$ kg/mm$^3$</td>
</tr>
</tbody>
</table>

Average temperature in human body is about 36.5 degree Celsius. Obviously, there should be consideration on temperature dependency. However, reported data on experiment of behavior in various temperatures are heavily outnumbered, so the effect of various temperature conditions is not included in this analysis.

In order to reproduce the experimental results, we make a model analysis model exactly as the same with experiment environment.

From the result by analysis, it is well observed that analysis result rapidly approaching experimental result at higher stress. In contrast, higher stress of analysis result gained at lower strain. Only the relaxation data at 700 Pa of experimental result is considered in analysis would explain this error. By calculation, we get an average error less than 18%, which might be negligible. However, observation on tangential of the graph and small errors lead to a conclusion that our approach of material properties is considerably relevance.

3. Method for Analysis

From analysis result by Nishimura and K.Chin, simulation of liver deformation must consider the effect of gravity acceleration $^{[2]}$. Correspondingly, to evaluate such hyperelastic materials or elastomers, which is said to have an instantaneous elongation, the analysis for any deformation mode at any time must be run with gravity effect is loaded and this is different from that of other rigid body analysis.

1) Gravitational Load Effect

Gravitational acceleration is quasi-statically loaded onto the liver. The direction of gravity acceleration is set regarding that a patient is laid down on bed. Beside liver, there are lots of organs surrounding it. However, for the first step level of research, only liver is considered. Liver model is placed on rigid surface with 0.1 of friction coefficient.

The FEM model as in Fig 2.1 is used and gravitational acceleration of 9.8 m/s$^2$ is loaded. The simulation result showed in Fig.2.8 tells that the gravity effects the initial position of any point in liver. If there are cancer cells in liver, the initial displacement by gravity acceleration effect of cancer position must be considered in order to program pre-operative surgical robot. Gravity acceleration also effects the liver displacement during needle insertion.

2) Simulation and Analysis of Needle Insertion

Some researchers who studied needle tip geometry also pointed out the effect of cone type tip $^{[4][5]}$. Accordingly, the cone type and the size and length of the needle is shows in Fig.2.9 as below. This needle model consisted of highly concentrated distribution of nodes at the tip and biasly less nodes at the other side of edge. The existence of lots of nodes, represents the contact condition well between needle and liver, and this could prevent penetration phenomenon. The method also prevents the need to mesh a finer element of liver and consequently decreases computational cost.

We will explain later on how we create cancer tissue properties.

1) Insertion without friction coefficient,
2) Insertion with friction force,
3) Insertion with existence of assumed cancer tissue.

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It is difficult to determine the effect of sharpness of needle, in order to cut liver tissues. Instead, there are some criteria that when satisfied, it would give the sufficient condition for liver to separate and tear off from
its rigidity of nodal forces. In our simulation, we set that whenever liver experiences more than 0.7% of total elastic strain, effected area will disappear visually, and all its element and nodal properties will no longer works in the simulation. This is different from fracture mechanic approach as the node tear-off part should separate within its node. This simple tear-off condition works very well virtually.

Cross-Section view of needle insertion consequence of 2nd analysis mode (contour: Equiv.Von Mises Stress)

1: With Needle

2. With out Needle

Result in Fig.2.10 shows that after the first cut, forces drastically dropped. Then, when it reaches and tend to cut next element, we observe that larger forces needed in pre-analysis in consideration of friction. Accordingly, we can partially determine the reacting forces during penetration and cutting phase as follows.

\[ f_r = f_d + f_c \]  \hspace{1cm} (13)

Where,

\[ f_d = \text{force during uncut phase} \]  \hspace{1cm} (14)

\[ f_{cut} = \text{forces during cutting phase} \]  \hspace{1cm} (15)

Which we can specifically determine as follows.

\[ f_d = f_l + f_c + f_{friction} \]  \hspace{1cm} (16)

Where,

\[ f_l = \text{reaction force by liver} \]  \hspace{1cm} (17)

\[ f_c = \text{reaction force by cancer tissue} \]  \hspace{1cm} (18)

\[ f_{friction} = \text{friction force} \]  \hspace{1cm} (19)

In deformation phase (uncut phase), forces are the sum of reaction force produced by liver and cancer tissue. While in cutting phase, beside reaction forces by liver and cancer tissue, there are also friction forces acting and clamping around the tip.

Fig.2.11 Forces Acting on Needle

3) Needle Insertion with Cancer Existence

Cancer material properties would be hard to model, because there is no reported data based on experimental result. However, it is well-known that most cancer tissues are usually harder than original tissues of an organ. Although not knowing the real properties of it, we created a set of properties for cancer by simply assumed that cancer material properties are 5 times harder than liver material properties. Accordingly, the value of each material constant in Eq.(12) is multiplied by 5.

From studies on liver cancer, we can consider that most cancers cases appear near the blood vessels in liver. This can be understood from the liver’s function in human body. By referring to anatomical chart, we created a clot of liver positioned at as shows in Fig.2.12.
For needle movement, it is assumed here needle is only allowed to move along its axis direction towards the center of cancer. Certainly, in real surgery, needle may experience deflection and the tip position will be a feedback to the system in order to navigate needle to its target. But in this paper we considered a comparatively rigid needle in order to study the deform behavior of liver.

![Graph showing reaction forces and analysis time](image)

**Fig.2.13 Reaction Force of Needle Insertion and Deformable Body Forces**

![Graph showing cancer displacement and needle displacement](image)

**Fig.2.14 Cancer Displacement from Initial Position and Surface Condition during Needle Insertion**

Fig.2.13 above shows the result of a plot of needle displacement and reaction forces produced by liver. The 'jaggy' plot in the figure is the effect of element roughness. Refer to 2.13, (i) show that when sufficient condition achieved, the element will disappear from the simulation. At this time, an empty space will appears which the needle will have nothing to stab. When this happened, reaction forces will falls in a time till it reaches the next element in (ii), or when the elasticity recovery of the certain element touches the needle’s tip. Deformable body forces (body forces of liver and cancer) confirmed the forces equation in pre-analysis. Friction forces were too small during penetration process, as the contact region between needle and liver were small. This is caused by liver’s elements itself.

**Fig.2.15 Needle Displacement and Cancer Displacement with Their Between Distance during Penetration**

Fig.2.14 and Fig.2.15 imply that even the distance between needle and cancer is shortening, but at the end, needle did not stab the cancer. Cancer displaced from its initial position due to large deformation before needle puncture the liver tissue. We summarized the causes in effecting the needle forces in static-analysis as follows.

1) Cancer Material Properties
2) Cancer Size/Shape
3) Cancer Initial Position (after gravity is loaded)

From reaction forces result in Fig.2.13, and by calculation produced in (13)～(19), we can predict and reproduce experimental result with 3D simulation method.

### 4. Conclusion and Future Works

We proposed a simulation method on needle insertion during cancer infected liver. The finite element solid model is made from sliced MRI images. Then we developed nonlinear soft tissue model of rubber-like approach using well-known strain energy method. The approach method seems to work very well to produce nonlinearity in soft tissue model of liver. Friction between the needle and tissue and separation and tear-off condition of element were simply assumed and the needle insertion simulation to consider a cancer was carried out. Cancer existence in liver also resulted in the need of new needle force modeling considering its material properties.

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