Computational Simulation of Catheter Motion in Hepatic Blood Vessels

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1. INTRODUCTION

Catheters are used for transarterial embolization of hepatocellular carcinomas and arteriovenous malformations. Several mechanical properties such as pushability and torquability are required for catheters. In a previous study, we developed a computer-based surgical simulation system to simulate a catheter inside blood vessels for treatment of the brain [1-3]. This system was developed in order to predict the course of approach to a lesion and to obtain numerical results and animations for surgical planning, intra-operative assistance and the design of new catheters.

In this study, we applied the simulation methods for intravascular surgery to the case of hepatic surgery. We evaluated the effects of the mechanical properties of catheters in hepatic blood vessels by numerical analysis. These methods are expected to be useful for analysis of the structure of catheters and may help guide the design of new catheters.

2. METHODS

The simulation models used in this study are shown in Fig. 1. The microcatheter model is composed of viscoelastic springs (3 degrees of freedom) and segments. We calculated the contact force vector between the microcatheter and the vessel, as well as the induced moment of each segment, and then determined the effects of these forces and moments on other segments. The motion of the microcatheter was represented by the Newton-Euler equations of motion. We measured the shape and the mechanical properties of a commercial microcatheter produced by GMA Co. Ltd., such as its outer diameter, bending shape and bending stiffness, and used the results as the simulation parameters. The outer diameter of the microcatheter was found to be 0.8 mm. In order to evaluate the effect of bending stiffness, we used two values for bending stiffness in the simulations, the exact measured value and a value twice as large as this.

In the simulation models, the proximal part of the microcatheter is initially inserted into the parent catheter, whose inner diameter is 0.2 mm larger than the outer diameter of the microcatheter. The proximal node of the microcatheter is then allowed to move along the y–axis at a constant speed (2 mm/sec) in the $+y$ direction. In other words, the microcatheter gradually emerges from inside the parent catheter. As the total length of the microcatheter is smaller than the displacement of its proximal end, it finally becomes completely released from the parent catheter. The parent catheter is fixed in position and it is assumed to be a rigid tube.

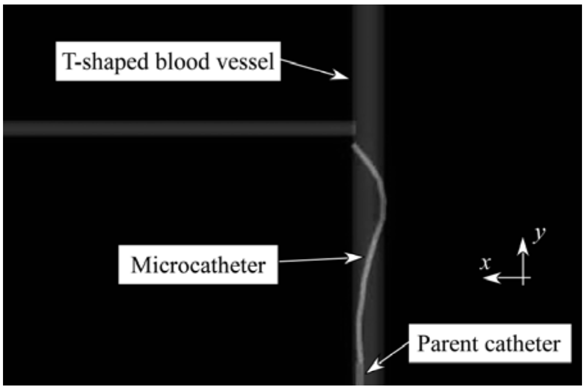

Fig. 1 Simulation models

The T-shaped blood vessel is modeled by two right circular cylinders with different radii, whose axes are perpendicular to each other. We used the position vector and the radius at points along the axes of the cylinders as the numerical data for the simulation. The diameters of the main and lateral artery are 4 mm and 2 mm, respectively. The axes of the two cylinders are assumed to be fixed.

Collisions between the microcatheter and the blood vessel are simulated and the contact forces are calculated based on the stiffness of the vessel walls. To determine whether there is contact between the microcatheter and the vessel, the distances between the joints and the tip of the microcatheter and the axis of the vessel were calculated. Contacts with the vessel walls could then be determined based on the diameters of the microcatheter and the blood vessel. Collisions between the microcatheter and the parent catheter were also considered in a similar manner.

Using the above models, we calculated the Newton-Euler equations of motion from the contact force at finite time steps, and evaluated the effects of the catheter parameters on its trajectory inside the T-shaped vessel.

3. RESULTS

For all conditions, the tip of the microcatheter was found to successfully enter the lateral artery from the main artery without becoming stuck, by a simple pushing motion at the proximal end. In addition, the trajectories of the microcatheter tip were found to be almost identical for different tip bending shapes and stiffness values.

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