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Examination of mitral regurgitation with a goat heart model for the development of intelligent artificial papillary muscle*

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***Abstract*— Annuloplasty for functional mitral or tricuspid regurgitation has been made for surgical restoration of valvular diseases. However, these major techniques may sometimes be ineffective because of chamber dilation and valve tethering. We have been developing a sophisticated intelligent artificial papillary muscle (PM) by using an anisotropic shape memory alloy fiber for an alternative surgical reconstruction of the continuity of the mitral structural apparatus and the left ventricular myocardium. This study exhibited the mitral regurgitation with regard to the reduction in the PM tension quantitatively with an originally developed ventricular simulator using isolated goat hearts for the sophisticated artificial PM. Aortic and mitral valves with left ventricular free wall portions of isolated goat hearts (n=9) were secured on the elastic plastic membrane and statically pressurized, which led to valvular leaflet–papillary muscle positional change and central mitral regurgitation. PMs were connected to the load cell, and the relationship between the tension of regurgitation and PM tension were measured. Then we connected the left ventricular specimen model to our hydraulic ventricular simulator and achieved hemodynamic simulation with the controlled tension of PMs.**

I. Introduction

We have been developing a sophisticated artificial papillary muscle for the alternative surgical treatment of valvular diseases in heart failure patients as shown in Fig. 1. Major efforts have been made for the surgical restoration of mitral valvular diseases, such as mitral valve prolapse or mitral regurgitation (MR) in recent years. The configurations in the continuity of the mitral apparatus and the mechanical interactions between valve and papillary muscles have also been reported by several investigators for the effective valve repair in patients with MR which demands an understanding of its mechanism in the individual heart [1-8]. Valve tethering from PM displacement is one of the important mechanical interactions in the appearance of functional MR. Then we developed an artificial PM using a sophisticated anisotropic covalent Ni-Ti shape memory alloy fiber based on the diagnostic controlling of PM dynamic displacement.

The aim of this study was to examine the functional MR with the tensions of PM in the isolated goat heart specimen model for the development of shape memory alloy fibered artificial PMs. The fiber in the artificial PMs was to be controlled by electric current supply synchronously with ventricular contraction. In order to establish the functional design parameters for the device, we performed a mock circulation test for functional MR under the steady flow circuit as well as the pulsatile hemodynamic conditions.

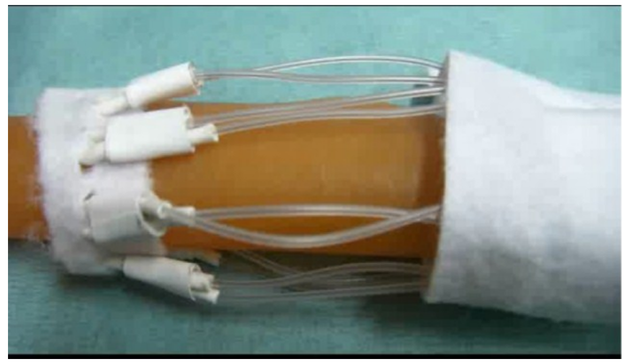

Figure 1. A prototype model of the artificial papillary muscle (PM) using anisotropic shape memory alloy fibers which can synchronize with the native myocardial contraction.

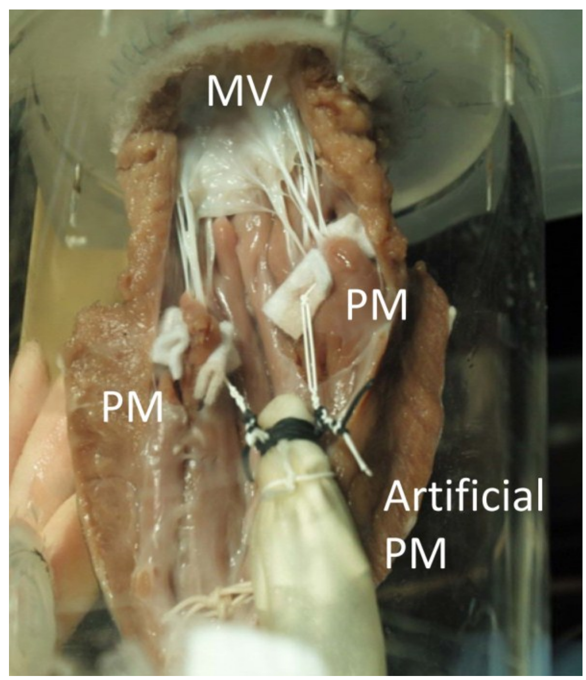

Figure 2. An example of the artificial PM and mitral valve model designed in this study

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II. MATERIALS AND METHODS

A. Isolated Goat Heart Model

Fresh goat hearts were isolated from goats, which weighed 42±10kg (n=9), after the animal experiments. Hearts were selected on the basis of the intact state of the left ventricles. These hearts were selected for the experiments by excluding the heart with hypertrophy in ventricular wall and septum by the echocardiography diagnosis. Hearts that had mitral valve prolapse or apparent MR were excluded. The 2D echocardiographic data were acquired from the heart prior to the experiment. Based on these mitral valve diameter, as well as ventricular diameter measurement, we sutured the specimen onto the polymer membrane in order to maintain of adequate anatomical structure. The right ventricle septal wall and a part of epicardial side of posterior wall of the left ventricle were resected. We sutured the isolated specimen including aortic root and left atrium with valves and PMs on the elastic polymer membrane at the basal position. Although we removed surgically most of the left ventricular for the reduction of stress retention among the specimen, the endocardial side of the left ventricular wall was retained between the leaflets and the papillary muscles for the sophisticated anatomically-identical reconstruction in the model. Each papillary muscle was connected to the load cell by surgical sutures. All the experimental procedure were reviewed and permitted by the Animal Experiment Ethical Committee of Tohoku University.

B. Steady Flow Test for Functional MR

The goat heart model secured in the casing was connected to the overflow tank circuit with the head of 100 mmHg filled with room temperature water (Fig. 3). The aortic root was firmly sutured to prevent the leakage from the ventricular chamber. We measured the leakage volume at the atrium i.e. the inflow portion of mitral valve by weighing method under the different PM tensile force. We adjusted the PM tension by the displacement of the load cell. We stretch PMs for 20 seconds by 4.9, 9.8, 14.7, 19.6 N and examined the MR at each condition. We obtained the mitral valve back flow as the summation of leakage volume at the left atrium-pulmonary vein port. The measuring port of which was exposed to the atmospheric pressure. The mitral valve inflow side was enclosed with the left atrial wall, and it was filled with the circulatory media. Then we examined the relationship between the leakage volume and papillary tension under the constant pressure gradient at the mitral valve.

C. Hemodynamic Examination using Ex Vivo Model Simulator

We also develop the pulsatile ventricular simulator for the examination of hemodynamics using the ex vivo model of the goat heart. The left ventricular chamber was connected to the hydraulic actuator which was capable of simulating the natural left ventricular volumetric changes by the originally developed numerical control (Fig. 4, 5).

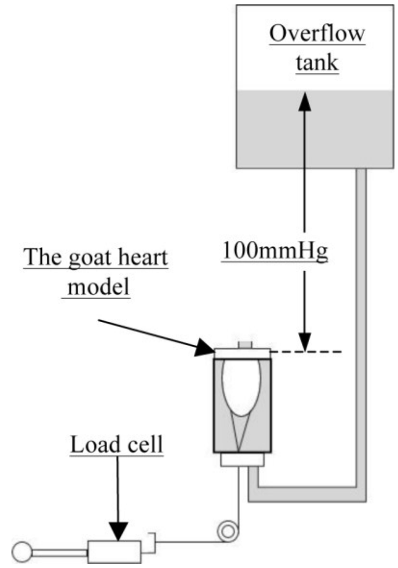

Figure 3. Schematic illustration of steady flow circuit with constant afterload of 100mmHg for the measurement of MR with tension of PMs.

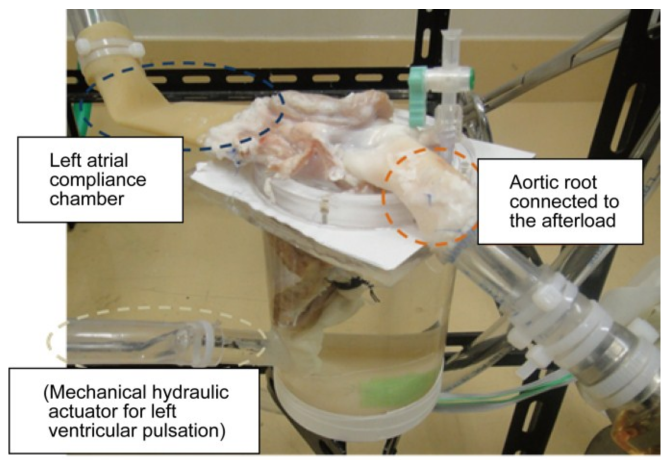

Figure 4. An example of the ex vivo ventricular model connected to the pulsatile hemodynamic simulator developed in this study.

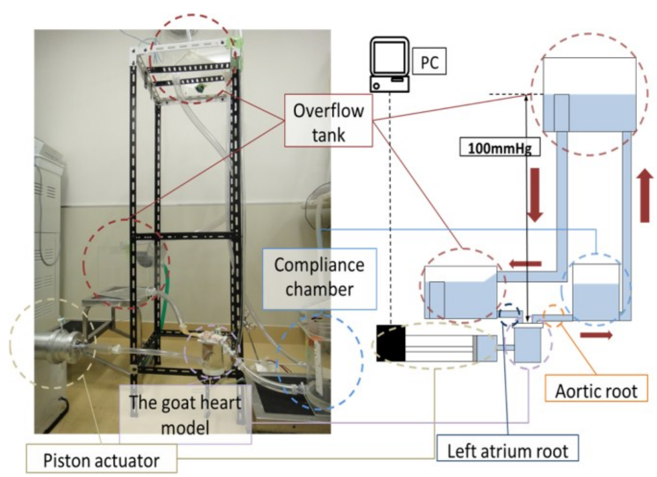

Figure 5. Whole view of the hemodynamic simulator with ex vivo system using the goat specimen heart model with hydraulic actuator

III. RESULTS AND DISCUSSION

A. The Left Ventricular Model using Goat Valves with PMs

Fig. 6 shows an example of the ex vivo model portion developed in this study for the examination of the artificial PM. Direct measurement of the displacement of each PM against the changes in the tension of the PM could be measured thought the transparent acrylic chamber.

B. Effects of PM tension on MR

The effects of the PM tension on MR were compared in the steady flow circuit under the condition of constant afterload. The MR flow decreased remarkably by the elevation of tension at PMs to around 15N as shown in Fig. 7. The incomplete mitral valve leaflet closure might be evaluated including PM dysfunction in the mock circulatory system, per se, decreasing the myocardial force acting to close the leaflet effectively. It is anticipated that the evaluation of valvular tethering effect could be achieved by the application of sophisticated artificial PMs for the reduction of tensions or MR by plicating the infarct region to decrease myocardial bulging towards improved surgical therapy. It was also anticipated that the tethering effects should be important for the structural recomposition of the mitral valve annulus and the ventricular apex including papillary muscles as well as hemodynamic simulation.

C. Hemodynamic Waveforms in the Pulsatile Simulator

We could also connect the specimen model developed in this study in the pulsatile mock circulatory system and perform the hemodynamic examination under the tensile force condition of PM at 15 N (Fig. 8). As a result, we achieved a hemodynamic simulation in the mechanical circulatory system, in which we installed the extracted specimens as components of the ventricular model. We demonstrated the ex vivo study investigating the effects of MR-PM tension. It suggests that the increase of PM tension to the normal left ventricular systolic pressure could reduce the functional MR. Therefore, it was indicated that this engineering approach using the extracted specimen could be useful for more sophisticated diagnosis in the surgical treatment process of severe MR as well as for the analysis of design parameters of the artificial papillary muscles. The mechanical interactions should be examined in the future models representing the infarct ventricular model toward improved therapy including tethering effects using our biomedical engineering approaches.

IV. CONCLUSION

We examined the MR with PM tensions in the originally-developed mock left ventricular model. We could establish the sophisticated design parameters for artificial PMs using shape memory alloy fibers.

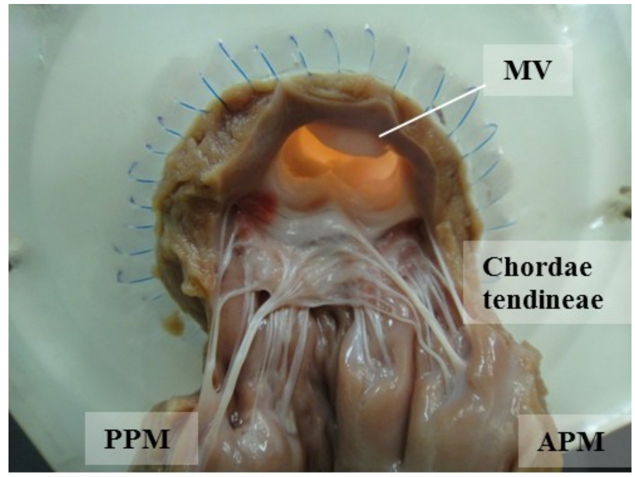

Figure 6. Epicardial view of the ex vivo mitral-PM model secured on the elastic polymer membrane using polymer sutures.

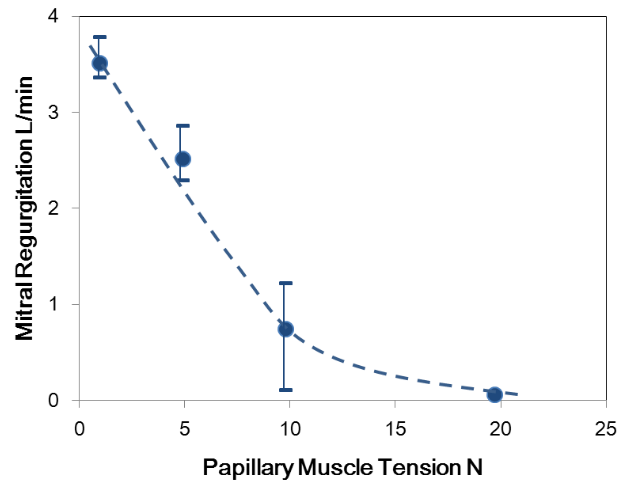

Figure 7. Changes in the static MR with PM tension obtained in the goat heart model.

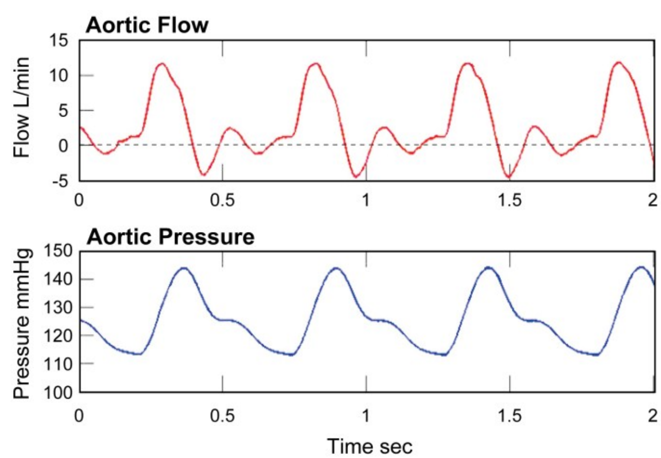

Figure 8. Hemodynamic waveform obtained in the ex vivo simulator using goat specimen ventricular model with the hydraulic pulsatile actuator under the constant PM tension of 15N.

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