Effect of right atrial contraction on prosthetic valve function in a mechanical pulmonary circulatory system

Yusuke TSUBOKO*, Yasuyuki SHIRAISHI****, Satoshi MATSUO****, Akihiro YAMADA***, Hidekazu MIURA***, Takuya SHIGA***, Mohamed Omran HASHEM*** and Tomoyuki YAMBE******

*Graduate School of Biomedical Engineering, Tohoku University
4-1 Seiryo-machi, Aoba-ku, Sendai 980-8575, Japan
E-mail: yusuke.tsuboko.a4@tohoku.ac.jp

**Department of PreClinical Evaluation, PreClinical Research Center, Institute of Development, Aging and Cancer, Tohoku University
4-1 Seiryo-machi, Aoba-ku, Sendai 980-8575, Japan

***Department of Medical Engineering and Cardiology, PreClinical Research Center, Institute of Development, Aging and Cancer, Tohoku University
4-1 Seiryo-machi, Aoba-ku, Sendai 980-8575, Japan

****Department of Cardiovascular Surgery, Graduate School of Medicine, Tohoku University
1-1 Seiryo-machi, Aoba-ku, Sendai 980-8574, Japan

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Abstract
Improving the inflow characteristics of the right ventricular function and pulmonary circulatory hemodynamics was essential for more precise evaluation of newly designed heart valves. To examine a pulmonary hemodynamics, the authors have been developing a pulmonary mechanical mock circulatory system. In this study, the pneumatically driven right atrium model was newly developed for clarifying the effect of atrial contraction on the dynamic behavior of pulmonary prosthetic valves. We focused on the hemodynamic behavior of the outflow mechanical heart valve of the right ventricle that could be affected by the right atrial dynamic motion. A medical-grade bileaflet valve was employed and installed into the outflow portion of the right ventricle model and examined its changes in hemodynamic behavior caused by the active right atrial contraction. With the active atrial contraction, hemodynamic waveforms of either the right ventricle or atrium were obtained using the modified pulmonary mock circulatory system. The characteristics with atrial contraction were well simulated as the natural hemodynamics. The right ventricular output increased by around 5% and the peak regurgitant flow at the moment of valve closing significantly decreased by the presence of the atrial contraction. Our mechanical circulatory system could simulate the end-diastolic right ventricular inflow characteristics. We found that the atrial contraction under the low pressure condition such as pulmonary circulation promoted earlier valve closing and prolonged closing duration of prosthetic valve. The simulation of right atrial contraction was important in the quantitative examination of right heart prosthetic valves for congenital heart malformation.

Key words: Pulmonary mechanical circulatory system, Atrial contraction, Pulmonary arterial valve, Pneumatically driven atrium model, Congenital heart disease

1. Introduction
Pulmonary artery reconstruction is commonly performed as one of the surgical treatments for congenital heart disease patients with pulmonary coarctation. This procedure is to replace the stenotic pulmonary heart valve such as hypoplastic right ventricular outflow tract by the artificial conduit valve in infants (Dos, et al., 2010; Miyazaki, et al., 2007, 2011). The atria perform three different functions during the various phases of the cardiac cycle, i.e. serving as reservoir during systole, passive conduit during early diastole, and booster function during late diastole (Mulder and
van der Wall, 2008). In pulmonary circulation which has one-fifth of pressure in comparison with systemic circulation, the effect of kinetic energy is relatively high. The authors have been developing a mechanical mock circulatory system for the evaluation of right ventricular outflow tract (RVOT) reconstruction (Suzuki, et al., 2012; Tsuboko, et al., 2015). In our previous study, a right atrium was modeled as a compliance tubing. A mock circulatory system with active contractile left atrium model has reported (Naemura, et al., 1997). However, there is no mechanical circulatory system which focused on atrioventricular contractile interaction in the pulmonary circulation.

In this study, we developed a pneumatically driven right atrium model to improve the inflow characteristics of the right ventricular function. The purpose of our study was to clarify the effect of atrial contraction on the dynamic behavior of prosthetic heart valves during active atrial contraction and non-atrial contraction.

2. Materials and Methods
2.1 Pulmonary mechanical circulatory system

A pulmonary mechanical mock circulatory system was designed to simulate a pediatric right heart circulation. A schematic illustration is shown in Fig. 1. The system consists of a cone-shaped silicone right ventricle (RV), a pneumatic-driven right atrium (RA) with a bileaflet polymer valve, a pulmonary valve chamber with a visualization port, a pulmonary arterial compliance tubing with a peripheral resistance unit, a pulmonary peripheral resistance unit, and a venous reservoir. The pulmonary arterial model was made by the silicone rubber sheet (KE-1300T, Shin-Etsu Chemical, Japan) that sandwiched the polymer sponge in it. The peripheral resistance of the pulmonary arterial model was adjusted at the resistive unit attached on the pulmonary arterial model.

![Schematic illustration of pulmonary mechanical circulatory system](image)

**Fig. 1 Schematic illustration of pulmonary mechanical circulatory system**

2.2 Pneumatically-driven right atrium model

To simulate a natural atrial dilation, pneumatically driven atrium model has been developed. In the study, we focused on a right atrium contractile function. We implemented the natural mechanical interaction between the right atrium and ventricle into the conventional mock circulatory system. The atrium model consisted of three key components as follows: a) an atrial chamber made of acrylic cylinder, the inner and outer diameters of which were 100 and 120 mm, respectively, b) a natural rubber membrane (Japan Elaster, Ltd., Japan) and c) a dome-shaped acrylic casing as an air chamber. The membrane was sandwiched, which separated the fluid and air chambers. The average height of the fluid chamber was 38 mm, and neutral volume was designed to be 300 mL. We used 1 mm thick ePTFE gasket sheets (Japan Gore, Ltd., Japan) for sealing between the casing and cylinder.

The RA and the RV could be driven synchronously under the different timing patterns with compressed air through
the air supply ports. An acrylic cylinder was placed around the RV. On the bottom of the cylinder, a solenoid valve for pressure release was attached. The solenoid valve (SMC, VXZ2240, Japan) was closed during RV systole and opened during RV diastole phase.

2.3 Control of atrioventricular interaction

We also developed a pneumatic driver for the active contraction and mechanical interaction between the right atrium and ventricle. The pressure in the air chamber was supplied and controlled by a regulator. We could control the period and timing of the contraction signal for the atrial model and the ventricle model by a pulse controller using a microcontroller board (Arduino, Arduino Mega 2560 R3, Italy). The system achieved the synchronous motion with ventricular driving signals in the atrium model, as well as its pumping rate and systolic function. During the systole and diastole phase, we supplied only positive pressure along with the passive dilatation of the atrial membrane without vacuum pressure. The right atrial pressure was provided intermittently which was followed by the ventricular chamber contraction. We set the driving mode for the atrioventricular interactive contraction. The driving diaphragm is shown in Fig. 2.

2.4 Hemodynamic examination

The clinical quality prosthetic valve has been tested in our system. We employed the mechanical bileaflet valve with the orifice diameter of 19.6 mm (St. Jude Medical, Regent, USA) and examined the effect of the right atrial contraction on its leaflet motions under the low cardiac output condition. Prior to the measurement, we installed the valve into the woven polyester vascular graft with the diameter of 24 mm (Maquet, Hemashield, Japan). The graft was coated by the latex rubber (Qua-Yu Kasei, L-5000) for the prevention of the endoleak from the wall before the valve installation.

The mechanical mock circulatory system simulated the following physiological pulmonary circulatory conditions. The normal pressure condition of the right heart circulation was shown in Table 1 (Bedesch et al., 2009; Nichols et al., 2011). The measurements were performed at 60 bpm. The diastolic duration was 600 ms. During systolic phase, the RV was contracted for 400 ms at a pressure of 25 mmHg. The RA was contracted for 150 ms at a pressure of 5 mmHg prior to the ejection of the RV. The interval of the RA (50 ms) was chosen to be similar to physiological conditions of the atrial contraction during a normal sinus rhythm (Damato et al., 1971; Scher et al., 1959). The systolic fraction of pneumatic RA and RV pumps were 15% and 40%, respectively. The mean RV output flow rate was set about 1.2 L/min as small sized children. We measured the right ventricle pressure (RVP), pulmonary arterial pressure (PAP) waveforms across the pulmonary valve and right atrial pressure (RAP) by the pressure transducers (Nihon Kohden, FX-300, Japan). The pulmonary flow was obtained at the outflow portion of the right ventricle using the electromagnetic blood flow probe (Nihon Kohden, FF-200T, Japan). These data were digitally recorded by the polygraph (Nihon Kohden, PEG-1000, Japan) at the sampling frequency of 1 kHz. A room temperature saline was used as a circulatory medium. Experimental conditions were shown in Table 2. The data were acquired during 10-continuous waveform periods and tested by t-test, and statistical analyses were performed using the statistical software (R Ver. 3.2.2 for Windows).
Table 1 Normal pressure ranges of the pulmonary circulation in healthy human

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Normal range</th>
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<tbody>
<tr>
<td></td>
<td>Systolic</td>
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<tr>
<td>RAP [mmHg]</td>
<td>-</td>
</tr>
<tr>
<td>RVP [mmHg]</td>
<td>20-30</td>
</tr>
<tr>
<td>PAP [mmHg]</td>
<td>15-30</td>
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Table 2 Experimental hemodynamic conditions for valve test

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>Pump rate [bpm]</td>
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<tr>
<td>Flow rate [L/min]</td>
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</tr>
<tr>
<td>Pneumatic driving pressure</td>
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<td></td>
<td>RV 25</td>
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<td>Systolic fraction</td>
<td>RA 15</td>
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<td></td>
<td>RV 40</td>
</tr>
<tr>
<td>Atrioventricular phase delay</td>
<td>200</td>
</tr>
</tbody>
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2.5 Valve opening area analysis

During the hemodynamic examination, the valve leaflet motion was obtained from the visualization port by using a high-speed video camera (Casio, EX-F1, Japan) at the image sampling speed of 300 frames/sec. Each valve leaflet motion was converted to sequential images. Then, images were binarized, and valve opening ratio were calculated (Wolfram Research, Mathematica 10.0, USA).

3. Results
3.1 Hemodynamic waveforms with/without atrial contraction obtained from our pulmonary mechanical circulatory system

By using the mock pulmonary simulator, we could reproduce the pulmonary hemodynamics for the examination of prosthetic heart valves. Hemodynamic waveforms of the right ventricle and the atrium model were shown in Figs. 3-5. As shown in the figures, the synchronous change in the right ventricular pressure with the right atrial contraction was increased. Transvalvular pressure gradient decreased at end-diastole and increased at early-diastole by atrial contraction (Fig. 4). The right ventricular output increased by around 5% with the atrial interactive contraction (Fig. 6). Moreover, an atrial contraction significantly decreased peak regurgitant flow at the moment of valve closing as shown in Fig. 7.

Fig. 3 Pressure waveforms of the mechanical bileaflet valved conduit (a) without and (b) with atrial contraction at 60 bpm obtained in the pulmonary mechanical circulatory system.
Fig. 4 Transvalvular pressure gradient between the right ventricle and pulmonary artery (a) without/(b) with atrial contraction at 60 bpm condition.

Fig. 5 Pulmonary flow rate of the mechanical bileaflet valved conduit (a) without/(b) with atrial contraction at 60 bpm.

Fig. 6 Mean pulmonary artery flow rate in the control and atrial contraction condition.
Fig. 7 Peak positive/negative flow rate in the control and atrial contraction condition.

3.2 Effect of atrial contraction on pulmonary valve behavior

Figures 8 and 9 show the changes in valve opening area and opening/closing speed calculated from the area detected from the high-speed video captured images under the conditions with/without the right atrial contraction. Each waveform was obtained from the similar driving condition of the mechanical circulatory system, and both of waves were correspondingly shown in the figure with the timing of RV systole. As shown in the figure, there was no discernible difference between the valve opening speed in each atrial driving condition, whereas the closing timing was earlier under the atrial contraction condition. Moreover, the peak closing speed decreased by the presence of atrial contraction.

Fig. 8 Changes in valve opening ratio in the mechanical bileaflet valve with and without atrial contraction.
4. Discussion

In this study, we developed a new contraction mechanism for the atrial model in the pulmonary mechanical circulatory system for the evaluation of valve behavior with the interactions between the right ventricle and atrial contraction. This is the first report on the prosthetic pulmonary arterial valve behavior under the different contractile conditions in the mock right ventricular circuit. We focused on the effects of contraction of the inflow conditions that could be affected by right atrial function in the mechanically driven pulmonary circulatory system. Our main interests were the effects of the dynamic atrioventricular interactions on the outflow valve dynamics which should be rightly and smoothly closed according to the right ventricular and end-systolic functional changes.

We made the mechanical circulatory simulation system for the pulmonary valve evaluation with the dynamic function of atrioventricular control. In the system construction process, firstly we constructed the components of the system by the polymer and plastic atrial and ventricular models with the valve chamber. Secondly, the right ventricular pressure and pulmonary arterial pressure were regulated by the peripheral resistive unit to maintain those values within physiologically normal ranges. For the determination of these basic parameters of the pressure, mean flow and the contractile timing or duration in the pulmonary circulation, approximately 20-30/0-5 (Systole/Diastole) mmHg of RV pressure, 1.2 L/min of pulmonary flow rate, and 150-200 ms of atrioventricular delay were adopted using data from literatures (Bedesch et al., 2009; Damato and Lau, 1971; Hamilton and Dow, 1963; Nichols et al., 2011; Scher et al., 1959). As the results, we could achieve the standard conditions of our pulmonary circulatory system to be 27/2 mmHg of RV P, 26/7 mmHg of PA P, 6 mmHg of mean RA P, and 1.3 L/min of pulmonary flow rate with the active atrial contraction. Therefore, we could successfully simulate the valve function under the physiological conditions.

The results from this study suggested that the atrial contraction might reduce the backflow in the closing phase because of the earlier start of the valve closure as shown in Fig. 8. The atrial contraction was pneumatically carried out by the phase control with the right ventricular diastole. Thereby, the end-diastolic increase and the early-diastolic reduction of RV pressure were obtained as shown in Figs. 3 and 4. Therefore, it was indicated that the right atrial contraction followed by the reduction of RV preload as well as the promotion of early closing of the pulmonary arterial valve might decrease the volumetric loading for the right ventricle. The presence of the atrial contraction may induce effective ventricular filling and ejection.

From our study, we think that we could explain the indirect mechanical relationships between the right ventricular function and the right atrial dynamic contraction. From the physiological point of view, the contractile function of the atria has a strong relation to the thrombogenesis or thrombosis (Williams, et al., 1967; Wolf, et al., 1991; Lim, et al., 2013). Our focus and the data from this study suggested that the dynamics is one of the other factors to promote total flow dynamics in the pulmonary circulation as well as systemic circulation with the capability of elimination of stroke.

Fig. 9 Changes in valve opening/closing speed in the mechanical bileaflet valve with and without atrial contraction.
In order to conduct the sophisticated evaluation of the diseased pediatric or adult pulmonary hemodynamics for the support of the surgical treatment using prosthetic heart valves, the optimal driving test conditions including physiological atrioventricular volumetric balances should be considered. The changes of the atrial contraction condition might be an important parameter for the evaluation of pulmonary valve function, and we will prepare the next stage with the variable settings of the atrioventricular function in pulmonary circulation. In our pulmonary mechanical circulatory system, we used room temperature saline as the circulatory medium. Fluid viscosity effects on the valve leaflet behavior followed by the pressure and flow changes should be examined in the future study that could simulate the natural blood viscosity condition as well as the atrioventricular power distribution during the interactive contractions.

5. Conclusions

The purpose of this study was to clarify the effect of atrial contraction on the dynamic behavior of prosthetic heart valves during active atrial contraction and non-atrial contraction. In order to clarify the effect of atrial contraction on the dynamics of the pulmonary arterial valve, a pneumatic driven right atrium model to simulate the RV inflow characteristics was developed. We could improve the pulmonary mechanical circulatory system and the atrial contraction might be effective for the evaluation of sophisticated RVOT valve design.

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References


