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Relation between Left Atrial Pressure and the Corresponding Pulse Pressure in the Helical Flow Total Artificial Heart

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***Abstract*— The present control method used in our helical flow total artificial heart (HFTAH) would only need four parameters. Nowadays, gauge pressure sensors are being used to obtain the pressure needed for control parameters. Nevertheless, there are also many following problems such as calibration, maintenance, offset drift and infection due to the skin-penetrative lines for the usage of gauge pressure sensor. Therefore, it is preferable to find another substitutional way instead of the gauge sensor to measure the pressure. In addition, with an eye to completing an implantable HFTAH, we would like to do without any lines through the experiment animal. Therefore, it was confirmed in this study that whether there is a relation between the left atrial pressure (LAP) and its pulse pressure (amplitude). Subsequently the mean value of LAP and its amplitude were quantified. There are two methods used in this study to process the data. Method one, frequency spectrum analysis, is to quantify the signals by getting the absolute value of amplitude for a fixed heartbeat analysis. Method two, by using the synchronous detection method, it is postulated to be more applicable to variant heartbeat data with 1/R control. By the relation of LAP and the pulse pressure acquired in the above two methods, as long as the amplitude of LAP is known by the absolute pressure sensor, it's able to obtain the mean value of LAP (for it suggests a linear relation). Therefore the characteristic could substitute one of the control parameter (that is the LAP), and the other three parameters will be acquired by estimation thus it doesn't need to measure them additionally. Consequently, it is expected that acquiring LAP by absolute pressure sensor for one of the control parameters could attain to an implantable HFTAH.**

I. Introduction

The total artificial heart (TAH) requires physiological control of the output responding to the metabolic demand of the body that changes with the condition of the body. In our helical flow TAH (HFTAH) using helical flow pumps [1], it adopts 1/R control [2] that is a physiological control method of a TAH. For the control system, three parameters, the mean of cardiac output (QL), aortic pressure (AoP) and right atrial pressure (RAP), are necessary as input parameters. Additionally, the mean of left atrial pressure (LAP) is necessary to balance the left and right blood pumps. Consequently, it needs four parameters, the mean of QL, AoP, LAP and RAP. Currently we are using electro-magnetic flow probe and pressure transducers to acquire data of the four parameters. However, these sensors are too big to be implanted in the body and thus require skin-penetrating pressure lines and cables. Besides, the skin-penetrating lines and cables would cause infection. To eliminate such pressure lines and cables, a small implantable sensor for LAP measurement is necessary. Since we can acquire the mean values of QL, AoP and RAP by using several estimation methods if only mean LAP could be measured. One solution is the use of an absolute pressure sensor, which is small enough to be implanted in the body and does not need a reference pressure (and thus no pressure line is necessary). However, it is not so easy to calibrate it once it is implanted in the body. The former study adopted the inflow suction (or sucking) as zero for the calibration [3]. However, the suction of the TAH is a phenomenon preferred to be avoided, hence it is better to use other substitution plan for absolute pressure sensor if a method goes well could be found without calibration. Therefore, we propose an alternative method in which mean LAP can be measured with its pulse pressure. To confirm the possibility of this mean LAP measurement, relation between the mean LAP and the amplitude of pulse pressure in LAP was analyzed.

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II. Materials and Methods

Concept of the mean LAP measurement

In the TAH, ventricles are removed but atria are left. However, atrial construction is lost because the ascending aorta is clamped and thus coronary flow is stopped. Additionally, atrial volume is a little bit smaller than the natural state because atrial appendages are ligated to prevent suction of atria to the inflow ports. In this condition, the atria work as reservoir bags of blood. They inflate in diastolic phase and deflate in systolic phase because the HFTAH generates pulsatile flow. Concerning left atrium, the motion of inflation and deflation in the left atrium is influenced by the blood volume reserved in the lung and compliance of the left atrium, and thus influences pulse pressure in LAP. If the blood volume reserved in the lung is much, which means high LAP, then the atrium keeps inflation with high LAP and deflating motion is small. In this condition, compliance of the left atrium prevents pressure drop in diastolic phase and consequently pulse pressure becomes low. On the contrary, if the blood volume reserved in the lung is little, which means low LAP, then the motion of the atrium becomes significant. In this condition, the compliance effect of the left atrium becomes small and consequently pulse pressure becomes high. Thus, mean LAP can be measured from the pulse pressure in LAP.

Data acquisition

Data utilized in this study were acquired from the HFTAH experiment goat. QL was measured with electromagnetic flow-probes (FT-130TB, Nihon koden, Tokyo, Japan) attached to the systemic outflow cannula. LAP was measured with pressure transducers (P23XL, Nihon koden, Tokyo, Japan) through the side tubes of the left atrial cuff. Data were sampled with the sampling rate of 200 Hz.

Because the TAH needs a control algorithm to vary with the physiological condition, the 1/R control is being adopted in our HFTAH. In the natural heart, it makes stable stroke volume per heartbeat when it suffers no great change physiologically. From that point we adopt the concept that is aimed to stabilize the cardiac output (CO). An algorithm is set to adjust the heartbeat that the CO could be corresponding with the physiological conditions [4]. The formula is showed below.

$$CO = \left(AoP_{(n)} - RAP_{(SET)}\right) \cdot \frac{QR}{AoP - RAP} + CP \cdot BW \cdot \left(AoP - AoP_{(n)}\right) \quad (1)$$

Data processing

The frequency spectrum of the LAP could be divided into 4 parts. The first is the low frequency signal band which stands for mean LAP. The second one is the respiration effective band. The third is heartbeat pulsation of LAP. The fourth is motor rotational effective band. The respirational rate in the animal experiment of the HFTAH was about 15 times per minute (0.25 Hz). The motor revolution speed was changed by the animal condition and thus the rotational effective band was not fixed. However, the motor revolution speed was faster than 900 rpm and the rotational effective band frequency was higher than 15 Hz. Because the HFTAH had been adopting 1/R control in animal experiment normally thus the heart rate was changed by the 1/R control. Moreover, due to each frequency spectrum band overlapped with each other, therefore it was not easy to divide them separately.

Two types of resources were used for data processing. The first type was a fixed heartbeat data that was without any control in the drive condition of the HFTAH. Because the rate of the heartbeat data was fixed, it was easier to divide the heartbeat pulsation of the LAP from the LAP frequency spectrum. The fixed heartbeat data contained 1,868,674 points by the sampling rate of 200 Hz (roughly three hours). We applied frequency spectrum analysis method to analyze the relation between the mean LAP and the amplitude of pulse pressure in LAP. The second type was with 1/R control in the drive condition of the HFTAH. Because it was more difficult to divide the heartbeat pulsation of LAP from the LAP frequency spectrum in this 1/R data, we applied two methods for data processing. One method was the frequency spectrum analysis method, used for the fixed heartbeat data analysis identically, the other was synchronous detection method.

Additionally, the mean LAP suggested here did not imply a constant value but a time-variant data. Because the characteristic of low pass filter (LPF) was to get rid of the noises but remain the dynamic feature, we used the LPF to obtain the mean tendency of LAP.

Practical and rapid tradeoff concerns were made for cutting off, thus the interval between the end of passband and the start of reject band was basically set to be 0.05 Hz. Besides, for the fixed heartbeat data it was adopted a rather narrower interval of 0.02 Hz which was more suitable for that kind of data due to the ease of analysis.

A. Fixed heartbeat data analysis by the frequency spectrum analysis

To get the mean LAP, a finite impulse response (FIR) LPF was applied to LAP. As for eliminating respirational effect, the end of passband frequency of LPF was set 0.18 Hz and the start of reject frequency of LAP was set 0.2 Hz.

On the other side, to get the pulse pressure of the LAP, a band pass filter (BPF) that put a FIR LPF and FIR high pass filter (HPF) together was applied to LAP, and then the result was made for calculating an envelope of the filtered LAP successively. Because the amplitude of the LAP pulse pressure had changed slowly, the LAP pulse pressure was considered as an amplitude modulation (AM) signal that the carrier signal was heartbeat pulse of LAP and the modulating signal was the mean LAP. The rate in fixed heartbeat data was set 100 beat per minute (bpm) and the frequency of the heartbeat was 1.66 Hz. Therefore, the conditions of filters were set as the following: the end of reject frequency of HPF 1.46 Hz, the start of passband frequency of HPF 1.48 Hz, the end of passband frequency of LPF 1.84 Hz and the start of reject frequency of LPF 1.86 Hz. For envelope calculation, we used square detection that is a means of AM.

Because the left atrium inflation and deflation were generated by the HFTAH pulsatile flow, the pulse pressure of the LAP was not only affected by the mean LAP but also affected by the cardiac pulse flow of the HFTAH. To eliminate the effect of the cardiac pulse flow change in the HFTAH, the pulse pressure of the LAP was normalized by dividing the pulse pressure of the LAP with the pulse flow of the QL (the flow corresponded to the pulsatile change). For the acquisition of the pulse flow of the QL, the same method used to get the pulse pressure of the LAP was applied to.

Because the pulse pressure of the LAP did not change in the low pulse flow condition, the pulse pressure of the LAP would be omitted on condition that the amplitude of the QL pulse flow was less than 3 l/min. For inflow suction, the relationship between the mean LAP and the amplitude of pulse pressure in LAP was not the same relationship as in normal condition. Therefore, if mean LAP was lower than -15 mmHg, the inflow state was considered as suction and the mean LAP would be omitted.

B. 1/R data analysis by the frequency spectrum analysis

By the 1/R control, the heart rate would be changed. If the heart rate is changing dramatically, it is impossible and unreasonable to get the pulse pressure of the LAP by the frequency spectrum analysis method, because the respiration effective band would overlap with the heartbeat pulsation. Therefore, we selected the stable heart rate data and analyzed them by the frequency spectrum analysis method. The heart rate range of the chosen 1/R data was from 80 to 100(equal to 1.35 Hz to 1.7 Hz).

To get the mean LAP, the same method used in fixed heartbeat data analysis method was applied to. As for obtaining the pulse pressure of the LAP and the pulse flow of the QL, the same method used in fixed heartbeat data analysis method was applied to except for the filter frequency was different. The filtration condition was: the end of reject frequency of HPF 1.1 Hz, the start of passband frequency of HPF 1.15 Hz, the end of passband frequency of LPF 1.9 Hz and the start of reject frequency of LPF 1.95 Hz. The normalization and ignoring method (omit LAP data lower than -15 mmHg) in fixed heartbeat data analysis method were also applied to.

C. 1/R data analysis by the synchronous detection method

The frequency spectrum analysis method was simple and easy to make use of; however, this method could only be applied to stable heartbeat data and thus it's with some restrictions. To solve this problem, we adopted the synchronous detection method that is one detection method of AM to the LAP and the QL for gaining the LAP pulse pressure and the QL pulse flow. The square waveform of systolic-diastolic indicator signal which was generated by the HFTAH driver was used as the reference (carrier) signal in the synchronous detection.

For quantifying the mean LAP, the same method used in fixed heartbeat data analysis method was once again applied to. The normalized and ignoring measures in fixed heartbeat data analysis method were also exerted.

III. RESULT

Figure 1 shows the fixed heartbeat data and Figure 2 shows the 1/R data. Figure 3 depicts the relationship between the mean LAP and the normalized pulse pressure of the LAP in fixed heartbeat data by the frequency spectrum analysis. This implies a trend that the amplitude of LAP pulse pressure is greater in the lower mean LAP condition.

Figure 4 and figure 5 describe the relationship between the mean LAP and the normalized pulse pressure of the LAP in 1/R data by the frequency spectrum analysis and the

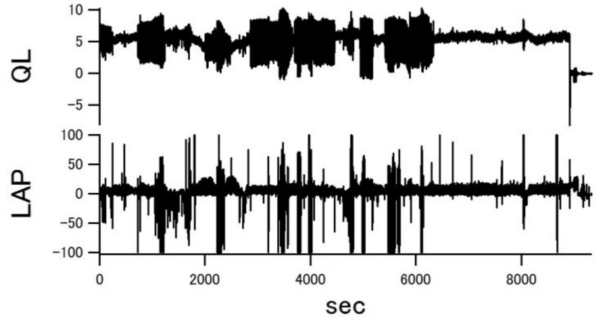

Figure 1. The LAP and QL of the fixed heartbeat data.

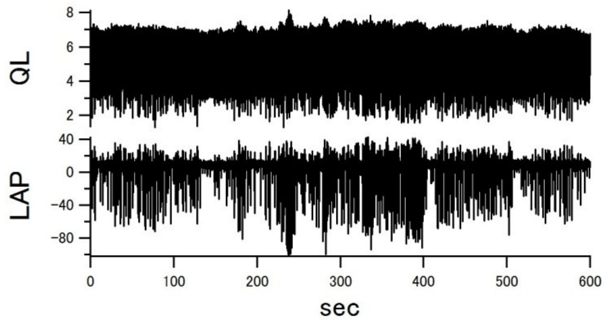

Figure 2. The LAP and QL of the 1/R data whose heartbeat was not fixed.

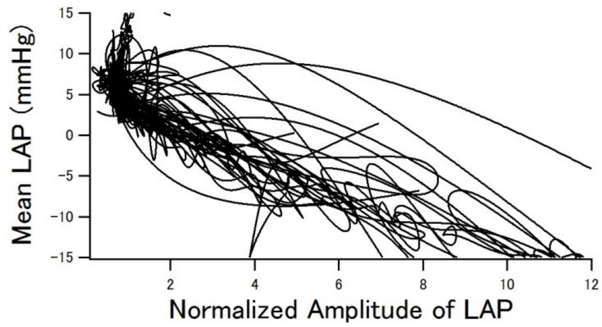

Figure 3. The relation between the mean LAP and the normalized pulse pressure (amplitude) of LAP. It used the fixed heartbeat data and the frequency spectrum analysis to acquire relation.

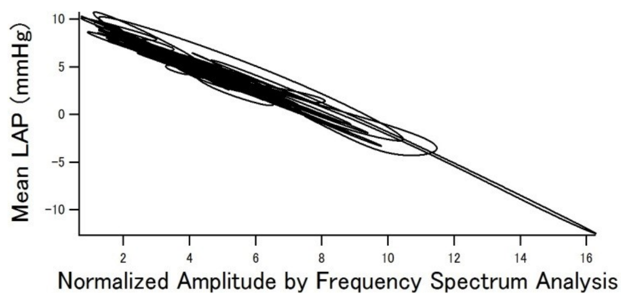

Figure 4. The relation between the mean LAP and the normalized pulse pressure (amplitude) of LAP. It used the 1/R control data and the frequency spectrum analysis to acquire the relation.

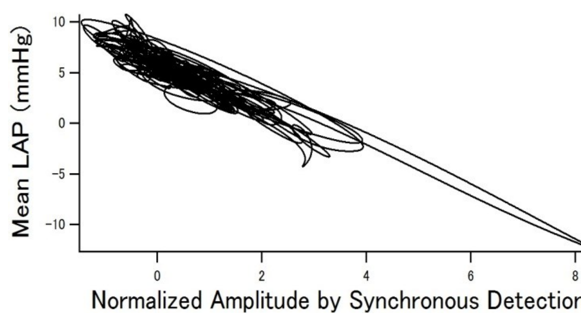

Figure 5. The relation between the mean LAP and the normalized pulse pressure (amplitude) of LAP. It used the 1/R control data analysis and the synchronous detection to acquire the relation.

synchronous detection method, respectively. These results also imply a trend that the amplitude of LAP pulse pressure is greater in the lower mean LAP condition.

IV. Discussion

The frequency spectrum analysis can be used for not only fixed heartbeat data but also for 1/R data. In this paper, the heart rate of the 1/R data was stable and the range of heart rate was from 80 bpm to 100 bpm. However, the range of heart rate in normal condition for animal experiments is basically from 70 bpm to 120 bpm. Therefore, the heart rate range limit of the frequency spectrum analysis is not a severe limitation and the method can thus be applied to the animal experiment data under 1/R control condition.

The phase of reference signal in the synchronous detection method is one of the important points. In this paper, the phase difference between the systolic-diastolic indicator signal used as the reference signal and the LAP or the QL signal was set as 0. Originally the LAP and the QL variations express a delay from the systolic-diastolic signal. By tuning the phase difference, the synchronous detection can be refined.

Ordinarily, the synchronous detection method is applied to a constant carrier frequency AM signal. Nevertheless, the heartbeat which was considered as the carrier signal of AM signal was not a constant. Meanwhile, the functional aspect of the reference systolic-diastolic signal of the synchronous detection was not 50-50% because it varies according to the animal condition. These effects must be further evaluated.

During the verification of other experimental data, we found that there were some data which cannot display a clear relation by the implement of both of our methods; therefore, we have to figure out its proper condition for implement and improve its availability. Currently, we consider that it might be the extent of the LAP which decides the applicability of the relation. In some data whose changes of LAP are not apparent, we could not obtain a clear relational plot by the two methods. Other factors like the phase difference in the synchronous detection, the influence of the suctions, the systolic-diastolic pulse, etc., are also being considered. We will furthermore investigate those data and adjust the analyzing tools.

The relation between the mean LAP and the amplitude of pulse pressure in LAP was still obscure though it was observed in both of fixed heartbeat and 1/R data. The LAP is composed of many signals and the pulse pressure in LAP cannot be completely separated by methods described above. By refining the separating methods for pulse pressure in LAP, the relation is supposed to be clarified.

In this study, it could be assumed that there exists such a relationship that the greater the amplitude is, the lower the LAP would be. Although we found that using frequency spectrum analysis is easier to obtain the desired linear relation, it is preferable to improve the design of synchronous detection method and thus it will be applicable to any kinds of heartbeat conditions.

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