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Algorithm of Copulsation Estimation for Counterpulsation using Pressure of VAD Outlet Cannula

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Abstract

The ventricular assist device(VAD) helps to reduce the overload against the patient's native heart(NH). The pulsatile VAD pumps out the ventricular blood to the aorta with pulsatile flow. If the VAD pulsates simultaneously with the NH, the ventricle of the NH could confronts abnormally elevated aortic pressure, and this could deteriorate the ventricle rather than assist to recover it. Thus counterpulsation algorithms to avoid copulsation have been adopted by many VADs, but these methods utilize electrocardiography or arterial pressure signals, which may have difficulties to acquire consistently for a long period.

In this study, the copulsation estimation algorithm for the counterpulsation is developed using the VAD outlet pressure signal. The VAD outlet pressure signal is good to maintain for a long time and the sensor part could be integrated to the VAD as a built-in module. From the VAD outlet pressure signal and its pump rate information calculated with Fast Fourier Transform, pulse peaks by the VAD and the NH were extracted and the next copulsation time at which the VAD and the NH would pulsate simultaneously was estimated. This estimation algorithm was implemented by using PC MATLAB software and tested for various pump rate conditions with mock circulation system. For each condition, the copulsation time was estimated successfully. Consequently, the results showed the possibility to use the outlet cannula pressure signal in the copulsation estimation.

Key words : counterpulsation, estimation of copulsation, pulsatile ventricular assist

I. INTRODUCTION

The implantation of a total artificial heart removes the native heart from the patient, while the implantation of ventricular assist device (VAD) leaves the heart as it is and assists the heart to reduce loads. Therefore, the VAD has an important advantage that it helps to recover the heart. The VAD pumps out the ventricular blood to the aorta and the continuous flow type VAD pumps blood out to the aorta with continuous flow, but the pulsatile VAD pumps with pulsatile flow. This pulsatile VAD has the possibility to pulsate simultaneously with the native heart (NH). In this case, the ventricle of the native heart confronts abnormally elevated aortic pressure because of the synchronized pulsation of the VAD with the native heart beat. This could increase afterload of the ventricle and could not make unloading of the ventricle rather than promote the recovery of the ventricle and aortic muscle[1-4]. To avoid this copulsation between the VAD and the NH, many VADs have adopted the counterpulsation algorithm using the electrocardiograph(ECG) signal or the arterial pressure signal[5-9]. In the ECG based counterpulsation, however, additional ECG electrodes are necessary and the maintenance of these electrodes for a long time is very difficult. Similarly, the arterial pressure based counterpulsation has same problems.

In this study, the copulsation estimation algorithm for the counterpulsation of the VAD and the NH was developed using the VAD outlet cannula pressure. The use of the VAD outlet cannula pressure has advantages as that it can be acquired for a long time without any discomfort of patients and the pressure sensor could be placed near to the VAD and could be integrated to the VAD as a built-in module. The copulsation estimation can give the time information when the copulsation would

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take place, and the copulsation can be avoided by delaying the VAD pulsation. This estimation algorithm is implemented by using PC MATLAB software and tested with mock circulation system for various pump rate conditions.

II. MATERIALS AND METHODS

The pulsatile VAD pumps out the drained blood to the aorta, thus the aortic pressure is the result of the blood pulse from the native heart as well as the VAD. Similarly, the pressure of the VAD outlet cannula is by not only the VAD pulsation but also the NH pulsation. In other words, the pressure signal of the VAD outlet cannula has the information of both the NH pulsation and the VAD pulsation. In this study, the copulsation timing of the NH and the VAD is estimated from the VAD outlet cannula pressure.

The mock circulation system as shown in Fig. 1 was used to simulate the situation of copulsation between the NH and the VAD. This mock circulation system corresponds to the systemic circulation and the electrical-hydraulic blood pump, Hemopulsa II (Biomedlab, Korea) was used for the function of the NH and the pulsatile extracorporeal blood pump, the T-PLS (New Heart Bio, Korea) was used as the VAD(Fig. 2) and connected to the NH in tandem.

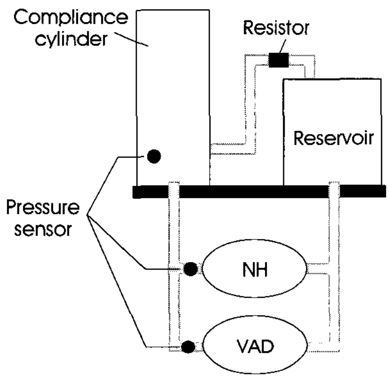

Fig. 1. The mock circulation system. The VAD is connected to the NH in tandem.

When these two pumps are operating, the pressure signal is measured at the outlet cannula of the VAD. The copulsation is estimated using this pressure signal as the following algorithm;

1. acquisition of the pressure signal at the outlet cannula of the VAD
2. extraction of the pump rate information of both the NH and the VAD using fast Fourier transform of the pressure signal
3. separation of the real time pulse peaks into two groups of the NH and the VAD, based on the pump rate information
4. estimation of peak points of the NH and the VAD
5. estimation of the next copulsation timing of the NH and the VAD

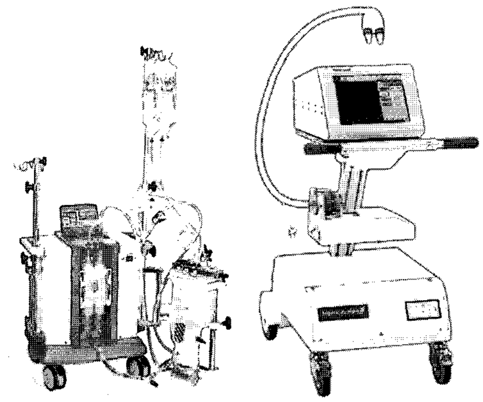

Fig. 2. Pulsatile VADs. (a) The T-PLS (New Heart Bio, Korea) was used as the VAD, (b) The Hemopulsa II (Biomedlab, Korea) was used as the NH.

The pressures were measured with pressure transducers (PSHBC1250, Sensys, Busan, Korea) and the measured signals were acquired with a data-acquisition board (EZAD-512, Elbio, Seoul, Korea) at a sampling frequency of 100Hz. The pressure waveforms were low pass filtered using butterworth software filter(4th order, 4Hz cutoff frequency). All estimation algorithms including fast Fourier transform were implemented by using MATLAB (Mathworks, Natick, MA, USA) software.

This algorithm was evaluated with various operating conditions. The pump rate of the VAD is fixed to 60 bpm and the pump rate of the NH was varied from 45 to 75 by 5 bpm. For each condition, the copulsation time was estimated and this estimated time was compared to real copulsation time measured using Hall effect sensors. The Hall effect sensor is placed in fixed part of the actuator and the permanent magnet is attached to moving actuator as shown in Fig. 3.

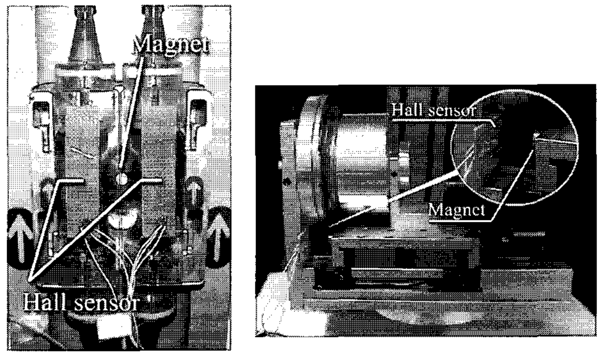

Fig. 3. The position of hall effect sensor. (a) The actuator of the T-PLS with Hall effect sensors attached at a fixed part and the permanent magnet attached at the moving part. (b) The actuator of the Hemopulsa II with Hall effect sensor attached at a fixed part and the permanent magnet attached at the moving part

Ⅲ. RESULTS

Fig. 4 shows the real time pressure waveform at the outlet of the VAD pump when the VAD is operated at 60 bpm and the NH is operated at 75 bpm. The pointed regions show the copulsations of blood pulses. Fig. 5 shows the fast Fourier transformed result of the VAD outlet pressure. In this step, two frequencies corresponding to the pump rates of the VAD and NH could be extracted. Fig. 6 shows the peak points of the VAD outlet pressure waveform. This waveform has pulse peaks by not only the VAD but also the NH. The solid lines and the dotted represent pulse peaks by the VAD and the NH, respectively. Since this copulsation estimation algorithm would be executed by the controller of the VAD, pulse peaks by the VAD could be discriminated from the other peaks by the NH. Using the information from the pulse peak time and the heart rate of the NH, the next NH pulse peak time could be estimated as Fig. 7. If there appear plural successive NH pulse peaks, the next peak time could be estimated as "case 1". Otherwise, if there appears one NH pulse peak time, the next peak time could be also estimated from the pump rate information as "case 2". The estimated copulsation time was compared to the real one measured by the Hall effect sensor signal.

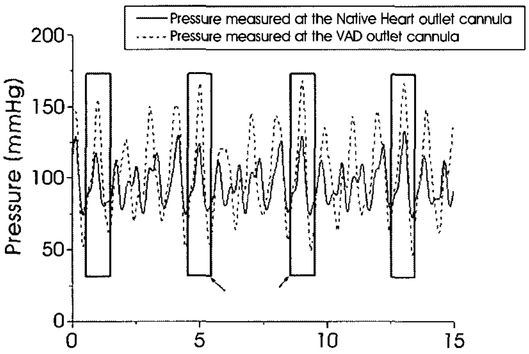

Fig. 4. The real time pressure waveform at the outlet of VAD and NH. Pointed regions show copulsations of the VAD and the NH.

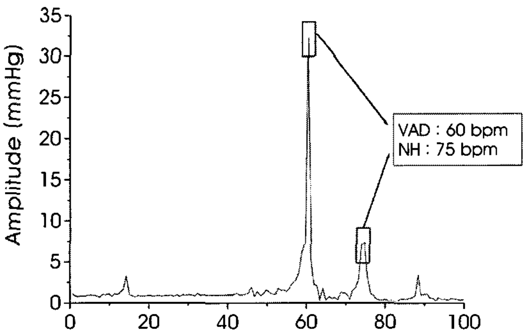

Fig. 5. The fast Fourier transformed result of the VAD outlet pressure in the condition of 60bpm operation of the VAD and 75bpm operation of the NH.

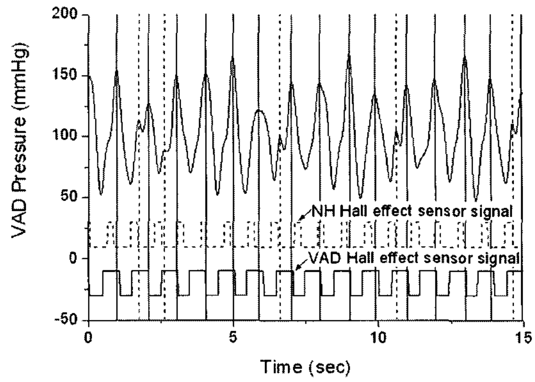

Fig. 6. The peak points of the VAD outlet pressure and Hall sensor signal output. The solid and the dotted lines represent pulse peaks by the VAD and the NH, respectively.

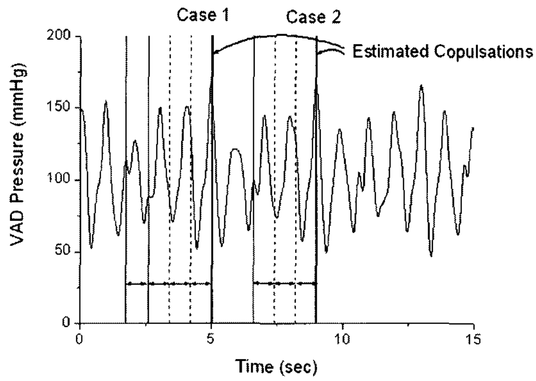

Fig. 7. Copulsation time estimation from the pulse peak time of the NH. In "case 1", the next copulsation was estimated from two adjacent peaks of the NH. In "case 2", the copulsation was estimated from the NH pulse peak point and the NH pump rate information.

Fig. 8 (a) shows the estimated result at the condition of 65bpm NH operation and 60bpm VAD operation. All copulsations were estimated without any error. Fig. 8 (b) shows the estimated result at the condition of 60bpm operation of the NH and the VAD. Since the pump rate of the NH and the VAD are equal and there is no pulse peaks between each VAD pulse peak, all pulses were estimated as copulsations. Fig. 8 (c) shows the result at the condition of 50bpm NH operation and 60bpm VAD operation. In this case, the NH pump rate is lower than the VAD pump rate, thus pulse peaks by the NH is less frequent. However, all copulsations could be estimated successfully. Fig. 8 (d) shows the result when the NH was operated at 45 bpm and the VAD was operated at 60bpm. The pump rate difference between the VAD and the NH is larger than the other cases. Thus copulsations were more frequent than the others. Although pulse peaks by the NH appeared less frequently than the other cases, all copulsations were detected successfully.

The term of copulsation means that two pulsations happen simultaneously and the pulse peaks generated at the same time.

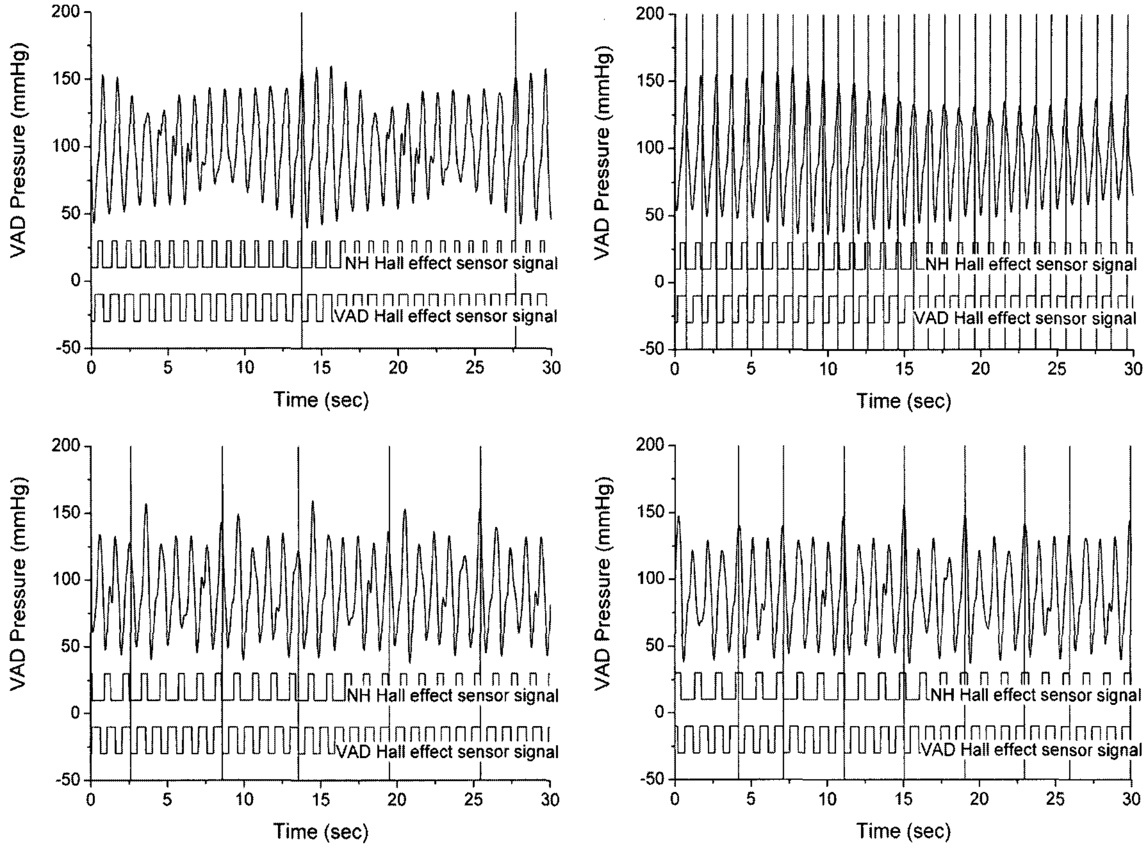

Fig. 8. The estimated result at the condition of
(a) NH 65bpm and VAD 60bpm
(b) NH 60bpm and VAD 60bpm
(c) NH 50bpm and VAD 60bpm
(d) NH 45bpm and VAD 60bpm

However, colliding pulse peaks with a short time difference, even they happens not exactly at the same time, could generate high afterload to the native heart and this should be also classified as the copulsation and should be avoided. The time difference between two colliding peaks which could be classified as copulsation is defined as copulsation time tolerance and Fig. 10 shows the results with different copulsation time tolerances. Fig. 10 (a) and (b) shows when the copulsation time tolerance is 0.1s and 0.2s, respectively. The time difference between the NH and VAD pulse peaks is smallest at the exact copulsation and this is increased as the NH and VAD pulsate with different phase and turns to be decreased as the NH and VAD pulse peaks come closer till the next exact copulsation. If the copulsation time tolerance is large, two pulse peaks with relatively large time difference are recognized as the copulsation, while the copulsation time tolerance is small, two pulse peaks with smaller time difference are recognized as the copulsation and this will be later than in the former case. Thus, the estimated copulsations in Fig. 10 (a) were later than Fig. 10 (b).

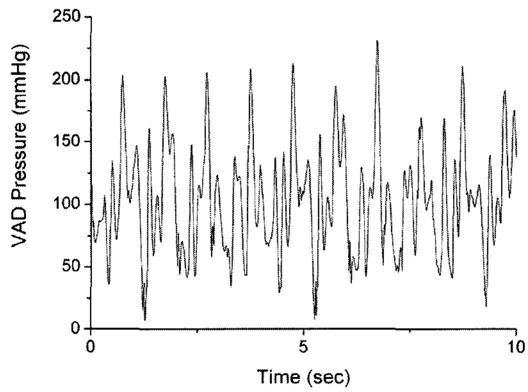

Fig. 9. The original pressure wave of the VAD. Pulse peaks regardless of actual pump pulsations must be filtered out to distinguish meaningful pulse peaks only by the VAD and the NH beatings.

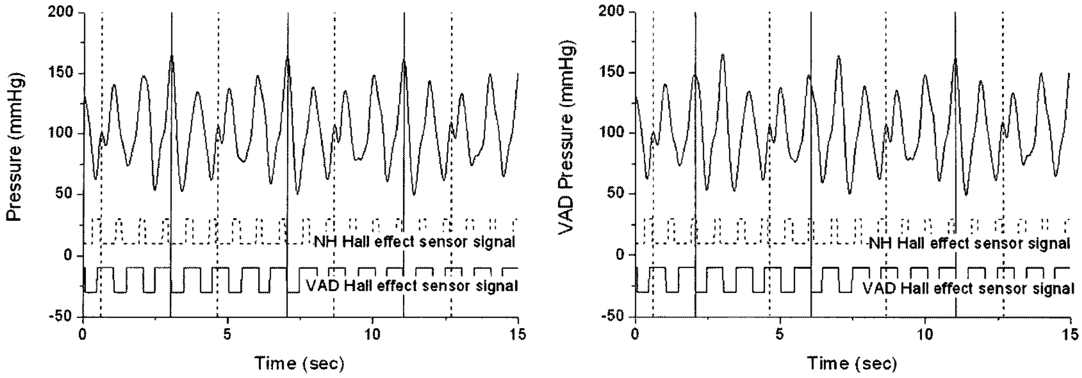

Fig. 10. Different results with different copulsation time tolerances. (a) the copulsation time tolerance is 0.1s. In other words, the time difference between an estimated NH peak and a VAD peak is smaller than 0.1s. (b) the copulsation time tolerance is 0.2s.

Ⅳ. DISCUSSION

The raw pressure waveforms have many pulse peaks by the noise as Fig. 9. Thus the low pass filtering is necessary to yield adequate waveforms which have meaningful pulse peaks only by the VAD and the NH beatings as Fig. 4. However, if the cutoff frequency is too low, many of meaningful peaks could be eliminated. Thus adequate cutoff frequency must be selected. In this study, the cutoff frequency was selected empirically.

The copulsation time tolerance determines how much adjacent two NH and VAD pulses can be recognized as the copulsation. If it is relatively large, less adjacent pulses could be recognized as the copulsation and the copulsation could be prevented earlier. On the other hand, if it is too small, almost cases but exactly simultaneous copulsation would be missed. Thus the copulsation time tolerance must be selected carefully according to the range of the copulsations which must be avoided.

The results showed the possibility to use the outlet cannula pressure signal in the copulsation estimation for counterpulsation algorithm. Moreover, since this method requires only one pressure sensor which could be integrated as built-in modult to the VAD, it would be useful in the situation as the installation of the ECG sensors or arterial pressure sensor is not affordable.

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