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A new method using ultrasound sensors to detect the diaphragm position of a ventricular assist device (VAD) was proposed. Two small ultrasound sensors of 2.4 mm diameter were attached to the outside surface of blood chamber of a pneumatic VAD. The receiving crystal received the ultrasound from the transmitting crystal reflected by the diaphragm. The diaphragm position was calculated by using geometric relation among two sensors and ultrasound propagation time. Validity of this method was evaluated in a mock circulation test under various driving conditions of VAD by comparing the ultrasound signals with driving pressure waveforms. The ultrasound signals could detect full-fill (FF) and full-eject (FE) status shortly before the spikes appeared on pressure waves, which are currently available to detect FE and FF but accompanies excessive extension of the diaphragm. This method would be helpful to avoid overloading of diaphragm. Linear correlation was observed between the output from VAD and blood volume calculated from the change of diaphragm position multiplied by the heart rate. This monitoring method of diaphragm of a VAD was proven to have advantages over the current method toward better control of a pneumatic VAD.

Key Words: Artificial Organ, Ventricular Assisted Device, Diaphragm, Ultrasound Sensor, Durability

1. Introduction

Recently, it was reported that ventricular assisted device (VAD), which is applied to severe heart failure patient, was used not only for bridge to recovery(1) but also for destination therapy(2). Although heart transplantation was started under organ transplant law in our country, absolute donor heart shortage prolongs duration of keeping on bridge using VAD. More highly durability is desired to VAD in present clinical use. In the case of management of the diaphragm type VAD, it was reasonable to know full-fill (FF) and full-eject (FE) state in order to recognize driving state in clinical use. The spike appeared on driving pressure waveforms were currently used in order to acquire this information(3). However, when this spike waveform occurrence, it is thought that the diaphragm was extended very much. When occurrence the spike on the wave, that means over-fill and over-eject state. Achieving high durability to this type VAD, it was desirable to avoid overload from this driving state. Therefore, we developed the new method, which was using the ultrasound sensor(4), (5), for recognizing FF and FE state ahead of over fill and over eject state. So, our first aim was to detect the exactly diagram position.

In order to test the feasibility of this method, we compared other methods, are using driving waveform to recognize FF and FE state and laser displacement meter to detect absolute value of diaphragm position. In addition, we investigated between the output from VAD and blood volume calculated from the change of diaphragm position multiplied by the heart rate. Using this method by very small ultra sound sensor, large probe (for example, electric magnetic flow meter) does not need to measure VAD flow. The patient was released from cramp.

2. Material

2.1 Ultrasound sensor

Figure 1 shows ultrasound sensor (Sonometrics Co. product) of 2.4 mm diameter, which is made by piezoelec-
Fig. 1 Ultrasound sensor

Fig. 2 Schematic diagram of measurement principle

Fig. 3 Schematic drawing of experimental apparatus

electric crystal. This sensor is very small and it is able to be detached and attached to blood pump housing part from outside. This sensor is used for cardiac function in vivo study.

2.2 Data processing and analytical software

We use the commercial software (SonoVIEW: Sonometrics Co. product) by data processing. This software was developed for cardiovascular analysis.

3. Method

3.1 Measurement principle

The schematic of measurement principle was shown (See Fig. 2). We used ultrasound reflected by the diaphragm. The diaphragm position in the VAD was detected by following procedure.

1) Setting the transmitting and receiving crystal (ultrasound sensor) on outside of housing of blood chamber.
2) Receiving crystal received the ultrasound from the transmitting crystal reflected by the diaphragm.
3) Ultrasound path was calculated from propagation time (Sound wave velocity: about 1540 m/s at water, blood).
4) Diaphragm position was computed by geometry relationship crystal position and ultrasound path. The computation was carried out by the following equation.

\[ x = \sqrt{\frac{p_d^2 + s_d^2}{2}} \]  

Where \( x \) is diaphragm position, \( p_d \) is ultrasound path, \( s_d \) is two sensors distance.

The installation location of transmitting crystal and receiving crystal were achieved good signal by trial and error. The distance between two sensors point was 15 mm.

3.2 Experimental method

In order to examine the validity of our ultrasound measurement technique, comparison with other conventional measurement technique was performed. First, for main purpose, we tested feasibility to detect FF and FE state. The conventional pressure wave method can only detect the FF and FE state. The Toyobo VAD was connected to an overflow mock circulatory loop tester. The driving unit was MobartNCVC(6). The working fluid was room temperature tap water. It was monitoring of diaphragm position by two ultrasound crystals. The driving pressure wave, which was measured from tap the located on drive line, was used for validity our ultrasound method (Fig. 3).

Next, our method was tested to detect the middle diaphragm position. We used the Laser displacement sensor method for the examination. The Laser displacement sensor (Keyence Co.) with highly resonance frequency was used to measure the dynamic diaphragm position was also used. The Laser light inflected by the housing shell of VAD. So, we removed housing shell of air chamber side, we could measure the diaphragm position by Laser sensor without inflection. But pump operation by driving unit was impossible. The diaphragm motion was caused by pressure changes in blood chamber, which was connected soft reservoir for taking water in and out.

Last, the pulsatile VAD is volume displacement type pump and therefore the between displacement diaphragm a beat and flow rate from VAD is assumed to have highly correlations. The flow rate from VAD was computed by the working time to fill up a volume (5L) and the pump output per beat was calculated by dividing flow rate by...
fixed heart rate.

4. Result

The positions from ultrasound method and from laser displacement sensor were in good accordance (See Fig. 4). In the case of partial fill state and partial eject state, which was shown various deformation of diaphragm, we also be able to use this method. The result was known the degree filling in pump to us by this method.

Measured diaphragm position from our method was compared with driving pressure (See Fig. 5). In the static state, the diaphragm position of maximum and minimum is 46 mm and 0 mm, respectively. These critical positions showed FF and FE states. The spike appeared on the waveforms of driving pressure at FE and FF states. The ultrasound method was more sensitive and the ultrasound signals reached the extreme value, which were measured at static state, before appearance of the spike.

Continuous monitoring of the positions of the diaphragm was carried out and the movement of the diaphragm was detected with the calculated stroke length of 46 mm.

Figure 6 shows the relationship between the displacement of diaphragm and cardiac output from VAD. There was high correlation \( r = 0.93 \), which showed the following linear equation, between the two.

\[
q = 1.83z + 0.42 \quad (2)
\]

where \( q \) [mL] was cardiac output per beat and \( z \) [mm] was diaphragm displacement.

By using signals from ultrasound method, we will be able to measure the flow rate from VAD.

5. Conclusion

1) It was possible to have detected the position of the diaphragm in pneumatic drive type ventricular assisted device by the very small ultrasound sensor.

2) There was high correlation between measured diaphragm displacement by ultrasound method and flow rate from ventricular assisted device.

References


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