AUTOMATIC CONTROL OF ARTERIAL AND ATRIAL PRESSURE FOR AN ASSIST PUMP BASED ON NONINVASIVE MEASUREMENTS

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During left ventricular bypass, it is important to keep an arterial pressure and atrial pressure at a physiological level to maintain the circulation and at the same time to recover the failing heart. It is essential to measure an arterial pressure and atrial pressure to control these parameters. However, chronic measurement of these parameters are difficult to obtain by conventional methods. We have developed the automatic control system of arterial pressure and atrial pressure based on only noninvasive measurements.

The control system consists of an optical diaphragm position sensor (1), pulse motor driven pressure regulator, air pressure transducer, and microcomputer. The control system regulates an arterial pressure and atrial pressure at a physiological level by adjusting driving pressure in proportion to the difference between desired pressure and noninvasively measured pressure.

MEASUREMENTS OF ARTERIAL AND ATRIAL PRESSURE

Careful analysis of the assist pump air pressure shows that the air pressure at specific momentary point when the diaphragm begins to move during a systole reflects pressure in proportional to the arterial pressure. When the drive air pressure is increased gradually during a systole, this pressure is transmitted to the blood in the pump through a flexible membrane and therefore blood pressure in the pump is also increased slowly. In the beginning of the systole the pump pressure is higher than the atrial pressure but lower than the arterial pressure. Therefore the diaphragm cannot move during this period. Once the pump pressure exceeds the arterial pressure, the diaphragm begins to move. The air pressure at this moment reflects the pressure proportional to the arterial pressure (Fig. 1). The diaphragm movement can be monitored by the optical sensor.

Atrial pressure may also be determined from the information derived from the assist pump air pressure. The principle of determining the atrial pressure from the drive pressure is the same as in measuring an arterial pressure (2).

In the arterial pressure measuring mode, microcomputer sends control pulses to the pulse motor attached to the pressure regulator to increase the driving pressure.
Fig. 1 Principle of pressure measurements gradually, and microcomputer receives a derivative of diaphragm movement signal (diaphragm velocity signal) and drive air pressure through the A/D converters. When the diaphragm velocity signal changes abruptly, i.e. an assist pump begins to pump blood into the systemic circulation against an arterial pressure, drive air pressure at that moment is fed into the microcomputer. After completion of the arterial pressure measurement, microcomputer makes pressure regulator return to the previous position by means of pulse motor, and normal driving mode is continued. Fig. 2 shows the arterial pressure measuring mode.

CONTROL SYSTEM

Block diagram of control system is shown in Fig. 3. Control system is consisted of pressure regulator, vacuum regulator, two pulse motors (one is attached to the pressure regulator and the other one is attached to the vacuum regulator), optical diaphragm position sensor, pressure transducer, and microcomputer. Pulse motor is used to rotate a pressure regulator or vacuum regulator. Optical sensor and drive air pressure transducer are used to measure the arterial pressure and atrial pressure (3).

Control parameters of the air driven diaphragm type assist pump are 1) driving pressure, 2) vacuum pressure, 3) driving rate, and 4) ejection duration. The developed control system enables manipulation of all these parameters.

We have fabricated automatic control system of arterial pressure and atrial pressure in which assist pump driving pressure is adjusted based on noninvasively measured arterial pressure and atrial pressure. The control system changes driving pressure in proportion to the difference between desired and measured pressure. Number of pulses to pulse motor, which rotates pressure regulator to increase or decrease driving pressure, is supplied in proportion to the difference between desired pressure and measured pressure.

\[ P_{\text{num}} = G \times (P_{\text{desire}} - P_{\text{measure}}) \]

where:
- \(P_{\text{num}}\); number of pulses to pulse motor
- \(G\); proportional gain
- \(P_{\text{desire}}\); desire pressure
- \(P_{\text{measure}}\); measured pressure

RESULTS

The feasibility of the method of obtaining arterial pressure by means of the optical sensor and drive air pressure transducer was intensively tested in vitro on a mock circulation. Fig. 4 shows the relation between the arterial pressure measured directly by a pressure transducer and the estimated pressure by the optical sensor and drive air pressure transducer with good correlation. The relationship between them is described through linear regression by equation:

\[ PD_s = 0.92 \times PA_O + 8.92 \ (r=0.996, n=9) \]

where
- \(PD_s\); estimated arterial pressure
- \(PA_O\); directly measured arterial pressure
Fig. 5 shows the relation between atrial pressure measured directly by a pressure transducer and estimated pressure by the optical sensor and drive air pressure transducer with good correlation. The relationship between them is described through linear regression by equation:

\[ PDs = 1.03 \times Pat - 1.19 \quad (r=0.996, \; n=8) \]

where: \( PDs \); estimated atrial pressure  
\( Pat \); directly measured atrial pressure

Fig. 6 shows the control of arterial pressure by adjusting the driving pressure. In the beginning of control, driving pressure is about 30 mmHg and mean arterial pressure is about 25 mmHg. However, a few minutes later, mean arterial pressure in regulated at about 100 mmHg as the result of control system. Driving pressure is increased to about 180 mmHg (control gain \( G=1.0 \)).

Atrial pressure is also regulated by adjusting driving pressure in proportion to the difference between desired atrial pressure and measured atrial pressure. Fig. 7 shows an atrial pressure control. Before the control atrial pressure is about 15 mmHg and driving pressure is about 90 mmHg. However, a few minutes later, atrial pressure is regulated at about 6 mmHg of desired level. This is achieved by increasing diving pressure at about 130 mmHg.

Fig. 8 shows atrial pressure control by adjusting driving pressure when atrial pressure abruptly changes. Mean atrial pressure abruptly increases from 6 mmHg to 15 mmHg (addition of water to the atrial reservoir), however, control system measures that high atrial pressure, and a few minutes later control system regulates atrial pressure at desired level by adjusting driving pressure at 150 mmHg.
Fig. 8 Atrial pressure control when atrial pressure changes abruptly

DISCUSSIONS

While knowledge of the arterial and atrial pressure is essential for controlling a left ventricular assist pump, chronic measurements of these parameters have traditionally been very difficult to obtain in assist pump implanted animal. The difficulty of obtaining accurate measurements is a result of drift, vascular erosion, thromboemboli and infection associated with implanted or percutaneous transducers. However, our method enables the arterial pressure and atrial pressure measurements without troubles of these conventional methods. The good correlations were obtained between the direct measurements and estimated values.

In the current measuring mode, slow increase of drive pressure is necessary for measuring arterial pressure. Because the derivative of optical sensor signal is about 70 msec behind the pump outflow. Therefore, when the movement of diaphragm is detected, drive pressure reaches already a plateau which has no relation to arterial pressure. One of the reason is that diaphragm begins to move from the peripheral part which is not monitored by the optical sensor. Therefore, if the start of pump outflow is detected by using several optical sensors in the pump, arterial pressure can be estimated in the normal driving conditions. Since arterial pressure decreases gradually according to the peripheral vascular parameters during diastole, noninvasive measuring system measures diastolic pressure which reflects more general hemodynamic condition than systolic pressure.

During left ventricular bypass it is important to keep the arterial pressure and atrial pressure at a physiological level to maintain the circulation and at the same time to rest the failing heart. The developed control system enabled stable automatic control of arterial pressure and atrial pressure by adjusting driving pressure.

The features of our developed control system are 1) to use the noninvasive measurements of output parameters (arterial pressure and atrial pressure), and 2) to regulate all drive parameters such as driving pressure, vacuum pressure, driving rate, and ejection duration.

The control system regulates the control parameters of an assist pump intermittently, because arterial pressure and atrial pressure are measured intermittently (time interval is a few seconds). However, intermittent control of driving parameters every a few seconds is believed to be enough to maintain the circulation.

CONCLUSIONS

We have developed the microcomputer based control system for left ventricular assist pump. The control system enables the automatic control of arterial and atrial pressure by adjusting the driving pressure in proportion to the difference between desired pressure and noninvasively measured pressure. The pressures are noninvasively monitored from the assist pump air chamber.

REFERENCES

3) Suzuki, Y., Mitamura, Y., Okamoto, E., and Mikami, T. Control system for assist pump based on noninvasive arterial and atrial pressure measurements Proceeding of 23 th Japan Soc. ME and BE, April 1984