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Balanced Cardiac Output Control for A Moving-Actuator Type Total Artificial Heart

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Introduction

One of the most important problems in the volumetrically coupled electrical total artificial heart (TAH) is to maintain balanced cardiac output between the left and right ventricles. This ventricular imbalance problem is caused by larger regurgitation through systemic arterial valve and the bronchial flow. Since the amount of regurgitation volume is changed according to pressure drop change across the aortic valve and the bronchial flow, the control ability to maintain must be adjustable over variations in preload and afterload.

Two methods to solve this imbalance problem are used widely. One is to add the volume compensation chamber which makes total system bulky and needs additional infusion port to refill air. And this balancing mechanism of volume compensation is used cooperatively with the passive filling mechanism of electric artificial heart of the Penn. state group[1]. The other is to use an inter atrial shunt(IAS) in the electrohydraulic TAH of the Utah group which has an active filling mechanism[2]. In this method, it is not well defined on shunt size and its potential of thrombogenesis.

We propose a new method to solve the ventricular imbalance problem for our moving actuator type electromechanical TAH which has an active filling mechanism.

We have developed a new moving actuator type TAH, the actuator of which moves along a circular trajectory to eject two ventricles alternately[3]. In the rolling cylinder pump, some problems were occurred in frictional energy loss and total pump size. In order to solve two major problems of circularly moving actuator type TAH, we modified mechanical mechanism as a pendulum like moving one[4]. The rotation of sun-planetary gears is converted into the actuator's pendulous motion by the fixed gear and shaft. In this modified moving-actuator type TAH, double sac type ventricles are used and their outer sacs are attached to a hoop which surrounds the pendulum actuator as shown in fig. 1. The hoop makes the outer ventricle expand smoothly as the actuator the actuator makes diastolic phase without creating high shear stress on the ventricle due to irregular stretching by a fixed attaching point.

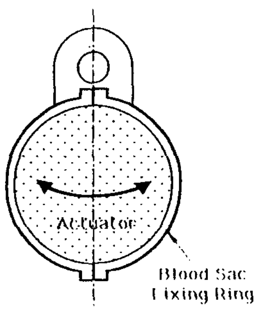

Fig. 1 Schematic diagram of pendulum type actuator surrounded by a hoop.

Theoretical Background

As the actuator moves around the fixed gear, stroke volume is determined by screening volume of the ventricle as shown in fig.2. When the actuator's motion is symmetric to the center of the fixed gear, stroke volumes of the left and the right ventricles are equal. Whereas stroke volume of the left ventricle become larger than that of the right if the actuator moves larger distance to the left side. The amount of stroke volume difference can be calculated with an ideal cylindrical model of the pendulum actuator. Stroke volume difference was calculated up to 15% with unsymmetrical motion of the actuator. The amount of air in variable volume space where we filled lubricant oil partially, is about 180 cc, its pressure fluctuation due to stroke volume difference can be also calculated approximately. Since volume size between the double sacs are very small compared to that of the variable volume space and lubricant oil is incompressible, stroke volume difference must be compensated by the air in Vv.

From the ideal gas law, we can find the pressure-volume fluctuation relationship between the left and the right systolic phase as like eq.(1)

$$P\,V_v = p\,v = C \quad \text{-----------} \quad (1)$$

where Vv is the size of variable volume space and C is a constant which is determined by initial pressure in Vv. p & v are fluctuating pressure and volume, respectively. For the typical case of our system, p is about 40 mmHg in order to make stroke volume difference by 10 cc(15%).

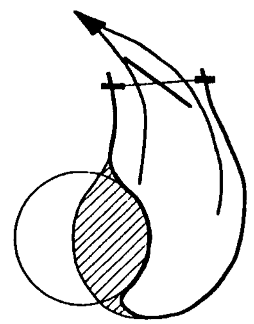

Fig. 2 Stroke volume calculation model of the moving actuator type TAH.

Materials and Methods

In order to move the pendulum actuator unsymmetrically, the center position of the actuator with respect to the fixed gear must be sensed by the electrical method. Therefore, we attached a hall effect sensor on the actuator housing which is made of stainless steel. And a small permanent magnet was attached under the bottom of the actuator to align with the hall effect sensor when it moves at the center of the fixed gear. Therefore the heart controller make the angular center of the actuator's pendulous motion shifted to accomplish an unsymmetrical operation, which generates stroke volume difference.

Cardiac output characteristics and performance of maintaining balanced stroke volume with a bronchial flow were tested under variations in preload and afterload.

In order to check compensation operation of the air in the variable volume space, aortic pressure(AoP), left and right atrial pressure(LAP, RAP) and the pressure in the variable volume pressure were measured during unsymmetrical operation of the actuator.

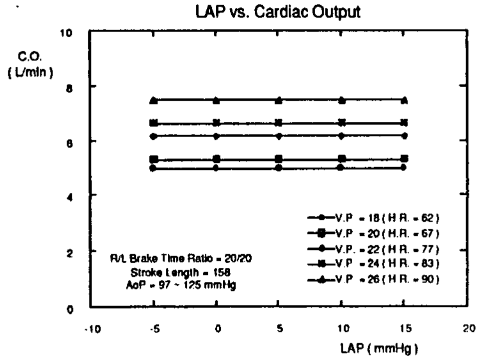

Fig. 3 Cardiac output is independent of the preload variations and changed with different velocity profiles.

Results

Fig. 3 shows that the pendulum type TAH has active filling mechanism i.e. cardiac output is independent of preload variations. Fig. 4 shows well balanced LAP & RAP at a normal hemodynamic condition (AoP = 100mmHg, PAP = 20 mmHg) in the Donovan type mock circulation system with bronchial flows.

Discussion

A new method to solve the intrinsic imbalance problem in the volumetrically coupled electromechanical moving actuator type TAH was proposed in this paper. Since the air in the variable volume space compensates the stroke volume difference in our pump, any separate compliance chamber which makes total size of the TAH bulky and cause complexity in surgery need not. And we also need not an additional infusion port to refill air into variable volume space. Since the amount of pressure fluctuation is 40 mmHg, it might reduce the energy efficiency of the total pump system. Efficiency test for our total pump system, therefore, is now performing. Automatic control algorithm which includes cardiac output response to preload and this balancing operation is also developing.

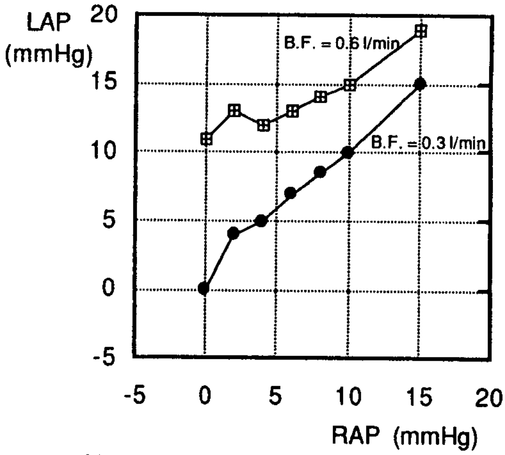

Fig. 4 Well balanced LAP & RAP
(Cardiac output = 6 l/min)
(B.F. means bronchial flow)

References

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