Design of A Pendulum Type Motor-Driven Blood Pump for Artificial Heart

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Abstract

A new version of moving actuator electromechanical total artificial heart was designed to improve total efficiency, durability, and fitting inside thoracic cavity.

As compared with our present type of the rolling cylinder actuator, this new model has a pendulum-type actuator with reciprocating motion around the fixed circular path, connected through the gear mechanisms to the motor. By using this mechanism, the efficiency and durability could be improved by replacing sliding mechanism with rolling contact elements. Also, the height of the pump could be decreased from 9cm to 7cm with static stroke volume 65cc.

With these improvements, we have implanted this new pump in human size animal (less than 70Kg weight).

Introduction

A new type electromechanical total artificial heart (TAH) has been developed since 1984 with two design objectives. The first is to reduce the total volume size of the pump to be implanted into the relatively small thoracic cavity of Orientals and to provide a high compatibility in fitting blood pump to the remnant of the natural atria and arterial vessels. The second is to provide the smooth operation of the pump actuator with low heat generation and high durability-that is high efficiency.

The basic idea of the new blood pump actuator is to eliminate the occupied space of the fixed-actuator in the conventional pusher-plate type blood pump. So a new system can be called as "moving-actuator" type pump mechanism.

In this mechanism, the actuator moves back and forth on the trajectories of circular path for alternative ejections of left and right ventricles. And the fitting problem of TAH to atrial remnants and arterial vessels could be improved by penduluous reciprocating motion on the circular path instead of the conventional pump's linear motion. [1,2,3] In the most motor-driven artificial heart system, the inflow ports are located for apart and the right and left outflow ports are in parallel direction each other. In our system, the interdistance between the right and left inflow ports is considerably reduced and the outflow ports' orientations are crossed each other with a sufficient angle for easy fitting to arteries. This factor is very important in surgical procedure. [4]

The first type of our pump system is circular motion type rolling cylinder moving-actuator blood pump. In the rolling cylinder pump, there exists frictional energy loss between the pump housing's guide bar and the actuator's end cap. Also the bottom rack under the cylindrical actuator increase the total height of the pump, thus the pump is not implantable inside the small chest of human-size animal with the body weight of less than 70 Kg.

The new type moving-actuator has the penduluous reciprocating motion of the actuator to correct the above two problems, while maintaing advantages of moving-actuator type's small total volume. [5,6] And we named the new blood pump as "pendulum pump".

We performed two acute animal experiments with new pendulum pump to evaluate the engineering feasibility of implantation of electromechanical TAH in human-size animal. [6]

Materials and Methods

A new pendulum pump actuator has a circular trajectories. The actuator goes a penduluous reciprocating motion between left and right ventricles. Figure 1 shows the schematic diagram of the pendulum pump.

Figure 2 shows the structural sketch of the acutator. Rotation of the motor's rotor is transferred to the actuator's planatary gear train which has gear ratio 1/64. With high reduction of rotation, very large torque is transferred to the 3rd torque plate and moving gear. Then moving gear moves back and forth on the fixed gear by revolution of motor shaft with action-reaction mechanism. Then total actuator moves back and forth between two ventricles for action of total heart.

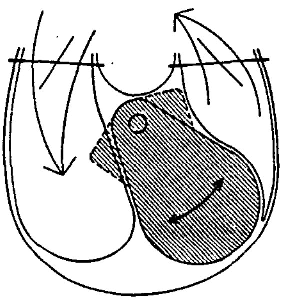


Figure 1. Schematic diagram of the pendulum pump

Figure 3 shows the perspectives of the actuator assembly and Table 1 lists the parts of mechanical components. All mechanical components are designed to guarantee five years operation without failure. For the purpose of lubrication and heat dissipation, the inner space of blood pump is filled with motor oil.

A high-torque burshless DC motor with small diameter and long length (Sierracin/Magnedyne 566-18) is chosen as an energy converter.

The detail mechanical properties and dimension of pendulum pumps and our old rolling cylinder pump are shown in Table 2. At new pendulum pump we could improve efficiency of the pump system to 19.5% and reduce the height of the pump from 9cm to 7cm.

And Figure 4-a shows the total actuator assembly and Figure 4-b shows mechanical parts for reduction.

The pellathane blood sacs have double membranes with the outer membrane attached to the actuator for diastolic augmentation by active suction. The air volume between the outer and inner membranes is adjusted to about 20cc to prevent any excessive suction pressure inside the inner sac. The total size and the stroke area of the left inner sac is larger than that of the right by 10% to diminish the imbalance problem, which is produced by the bronchial recirculation and valve regurgitation. [6]

Invitro and Invivo Experiments

Mock circulation test was performed using a Donovan

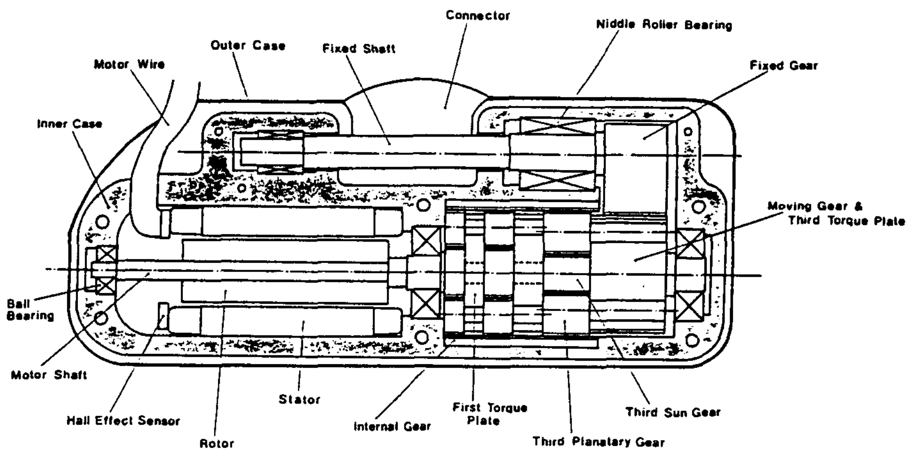


Figure 2. Structural sketch of the pendulum pump actuator

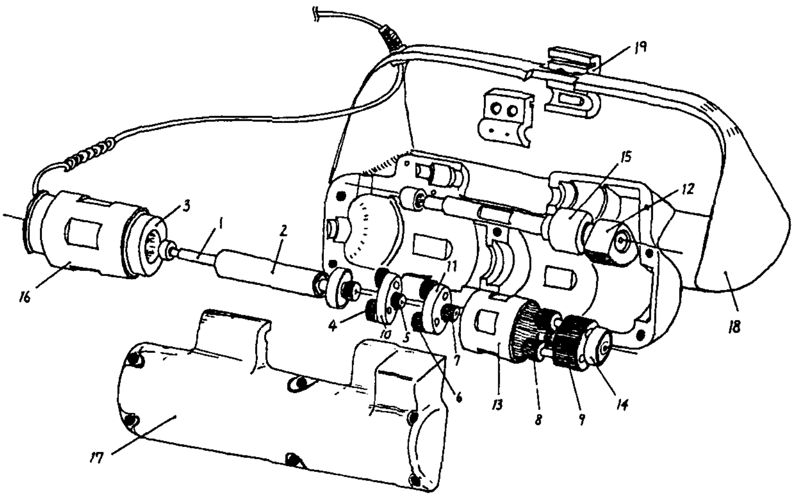
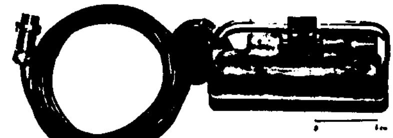


Figure 3. Perspective view of the actuator assembly

No.	Part Name	Materials	Qt
1	Motor Shaft & 1st Sun Gear	SCM-4 S/M 556-18	1
2	Rotor	S/M 556-18	1
3	Stator	SCM-4	1
4	1st Planetary Gear	SCM-4	3
5	2nd Sun Gear	SCM-4	1
6	2nd Planetary Gear	SCM-4	3
7	3rd Sun Gear	SCM-4	1
8	3rd Planetary Gear	SCM-4	3
9	Moving Gear & 3rd Torque Plate	SCM-4	1
10	1st Torque Plate	SCM-4	1
11	2nd Torque Plate	SCM-4	1
12	Fixed Gear & Shaft	SCM-4	1
13	Internal Gear	S45C	1
14	Ball Bearing		3
15	Neddle Bearing		2
16	Motor Outer Case	S45C	1
17	Inner Case	Polyurethane	2
18	Outer Case	Stainless Steel	1
19	Connector	SCM-4	2

Table 1. List of Mechanical Parts

(a)



(b)

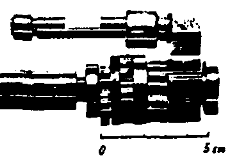


Figure 4. Pictures of (a) the total actuator assembly, and (b) the mechanical parts for reduction of rotation

like system. Pressure at five sections inside the pump were measured using COBE pressure transducers; the variable volume pressures between the right and left sacs, ventricular pressures inside two inner sacs, the pressure between double membraned of left and right sacs.

Two acute animal experiments were performed using the pendulum pump with a Coridale sheep (50 Kg weight) and a male calf (70 Kg weight). [6]

Results

The reduction of power consumption at no load condition

Dimension						Mechanical Properties					
Pump	Height (mm)	Length (mm)	Width (mm)	Volume (ml)	Weight (gr)	Reduction Gear Steps	Reduction Gear Ratio	Max. Motor Speed (RPM)	Motion Type	Torque Transferation Mechanism	Efficiency of Total Pump (%)
Rolling Cylinder Pump	90	100	110	990	810	2 steps	28:1	1600	Circular Trajectory	End Caps and Guide Bars & Racks	11.0
Pendulum Pump	70	130	70	640	980	3 steps	64:1	3800	Penduluous Reciprocation	Fixed and Moving Gear	19.5

Table 2. Comparision of the Dimension and the Mechanical Properities of two Pumps

Control Parameter Stroke Length - Velocity Profiles	Ratio of Power Reduction (%)
100 - 25	13.3
150 - 25	25.5
190 - 15	16.1
190 - 20	13.8
190 - 25	11.2
190 - 30	18.2
Average	16.4
Pump Efficiency	19.5

Table 3. Comparison of the motor power consumption between the pendulum pump and the rolling cylinder pump at no load condition and its efficiency (Pump efficiency was calculated at AoP = 100 mmHg)

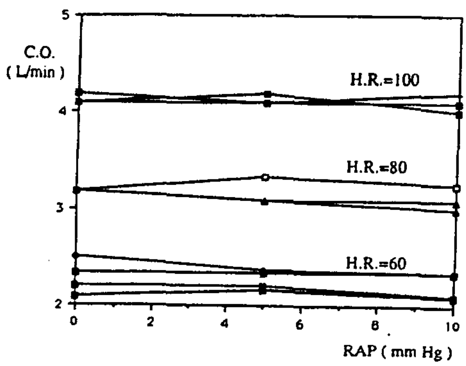


Figure 5. The relationship between RAP and cardiac output at various heart rates and constant stroke length in the mock circulation system

for the pendulum pump as compared to the rolling cylinder pump shows at Table 3. And the efficiency of the new pendulum pump is more than 19.5% at normal hemodynamic pressure condition. During experiments, our new pendulum pump actuator goes very smooth opertaion with very small mechanical wear. Figure 5 shows the relationship between the atrial pressure and the caridac output at various heart rate. This constant relation shows that the pump operates at full-fill range even at low level of atrial pressures by the disastolic augmentation of the double membranes in both sacs.

So we can conclude that the new pendulum pump actuator is fittable for TAH actuator without large defects.

Figure 6 shows LAP,RAP,the suction pressure and the pressure inside the inner sac of the right ventricle in mock circulation system. The volume change between the inner sac and the outer sac can produce a negative ventricular end-diastolic pressure of -10 mmHg even at low atrial pressure for moderate degree of active filling. Figure 7 shows same pressure at calf experiment.

We could implant the device inside the thoracic cavity of a 70 Kg calf without any difficulty. Experimental results of two animal experiments are summarized in Table 4.

Discussion

By moving-actuator type pump with the pendulum motion mechanism, we could decrease the total size of the electromechanical TAH and increase the total efficiency of pump actuator. So we could implant our TAH to human size animal.

In preliminary acute experiments, we operated the pump at

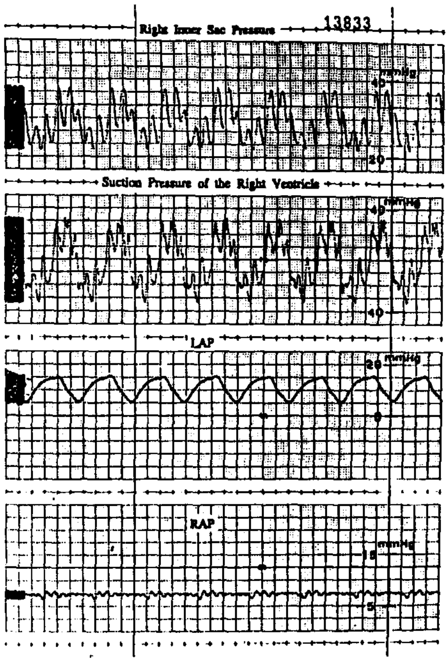


Figure 6. Waveforms of LAP, RAP, suction pressure and inner pressure of the right ventricle in the mock circulation system

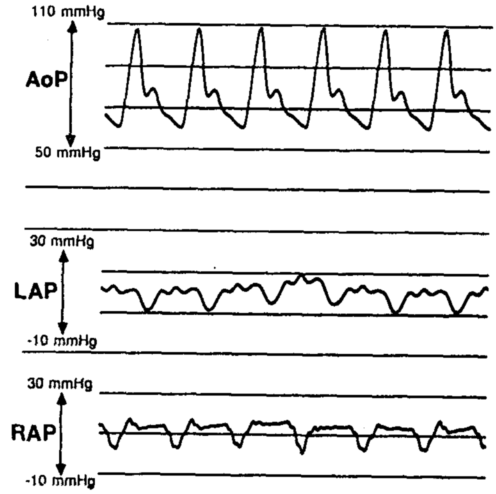


Figure 7. Waveforms of AoP, LAP, RAP at invivo test

Date	Animal	Weight	EXP.	Size of the Pump	Operation Time	Cuase of Death
Feb. '90	Coridale Sheep	50 Kg	Acute TAH	not fittable	5 hours	Sacrificed
Feb. '90	Calf	70 Kg	Acute TAH	good enough	12 hours	hypoxia, low C.O.

Tabel 4. Summary of Animal Experiments

low cardiac output of 3 l/min with heart rate of 80 BPM when the mean arterial pressure was 100 mmHg. This low cardiac output state was caused by the shortened operation stroke length than the design value to avoid any breakages of the polyurethane acutuator inner case of the present prototype molel. However, we will be able to make this inner case using duralumin to guarantee the pump's full stroke length and the designed cardiac output of 7.5 l/min at heart rate of 90 BPM, while maintaining the total size of the pump.

The variable volume space in our pump can be considered as any residual volume existing between two sacs inside the pump housing chamber, after excluding the actuator and its lubricating oil volumes. This variable volume is about 150cc in our pump, which is comparable to the compliance chamber volume of other groups' alternating pusher-plate type of TAH. [7] Therefore, with this similar size of internal variable volume, the pressure changes in this space can be minimized to ± 10 mmHg level, even with different stroke volumes of left and right sacs. Due to this small pressure change and the separation of blood sac from the variable volume space by double membranes, the inflow is sufficient by diastolic augmentation even at low atrial pressure level. Thus the LAP and RAP could be maintained below 15 mmHg level by having different stroke volumes of left and right sacs and full-fill operation of both sacs without any external compliance chamber. Our flexible polyurethane pump housing may also contribute to diminish the imbalance problem of TAH.

By changing the gear train mechanism and fixure method, improved pendulum pump is designed newly, and being fabricated. This new type has smaller dead space than old type, so total size of pump will be more reduced. In the old version of pendulum pump actuator, sliding friction loss was minimized by eliminating the guide-bar and end-cap. But there was still remained the thrust friction loss. In the new version of the pendulum pump actuator, thrust journal bearing is adopted for minimizing the thrust friction loss. So that new version of pendulum pump actuator will have at least amount of friction loss, and we can anticipate that the total efficiency will be more than 30%. Figure 8 shows the structural sketch of the new version of pendulum pump actuator. Total volume of actuator is reduced about 30% than that of the old version of pendulum pump actuator.

In conclusion, our moving-acutator pendulum pump actuator shows the engineering feasibility of the implantable TAH inside human chest cage. This implantation of the electromechanical pump inside the thoracic cage of the human-size animal (less than 70 Kg of body weight) is the first reported case in our best knowledge.

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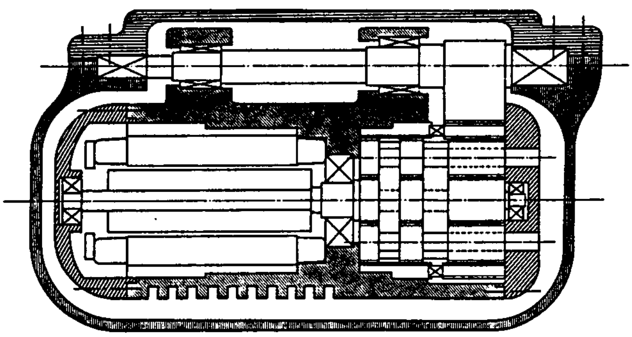

Figure 8. Structural sketch of the latest version of the pendulum pump actuator