A Simplified Model for Compliance Determination of the Moving-Actuator Type Totally Implantable Artificial Heart

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ABSTRACT

In this paper, we present a simplified model for compliance determination of the moving-actuator type totally implantable artificial heart (TAH). The modeling equations are derived from the mechanics and geometry of the TAH components. The interventricular pressure and volume are computed for determining the compliance of the interventricular space using this model. The model is capable of generating realistic hemodynamic variables such as the left atrial pressure and interventricular pressure and is proved to be acceptable. This model can be used as an initial step for analyzing characteristics of the moving-actuator type TAH.

INTRODUCTION

One of the main requirements for developing an electromechanical TAH is preventing atrial collapse. The atrial collapse may result from the generation of excessive negative pressure to fill blood in the diastolic sac. To accomplish this requirement, at first, we filled some amount of air into the interventricular space. This mechanism did not need any extra-compliance chamber and the system was modeled as a set of mechanical equations[1].

However, we have further developed a new system to increase the compliance of the interventricular space, i.e., the compliance of the TAH. A part of the rigid housing of the TAH was replaced by the flexible polymer membrane and this flexible part could expand or compress as the pressure of the interventricular space varied. In the result, the compliance of the TAH was increased to further prevent the atrial collapse[2].

In this paper, we have suggested a simplified model for compliance determination of the new TAH.

METHOD

Our TAH model consists of the following three components: the interventricular space, the left blood sac (the left ventricle), and the right blood sac (the right ventricle). The volume of the interventricular space is geometrically the residual volume of the air filled in the TAH. This volume is defined as the residual volume when the volume of both blood sacs, the volume of the actuator, and the volume of the lubricating oil are subtracted from the total volume of the TAH.

For simplicity, the both blood sacs and the actuator are considered as three cylinders. We also regard the air in the interventricular space is always following the ideal gas equation. From this model the instantaneous volume and pressure of the interventricular space is derived as follows:

$$P_{ivs} = \frac{-\{V_t - (V_d + V_s)\} + \sqrt{\{V_t - (V_d + V_s)\}^2 + 4nRTC_w}}{2C_w} \quad (1)$$

$$V_{ivs} = V_t - (V_d + V_s) + C_w P_{ivs} \quad (2)$$

where, P_{ivs} ; the interventricular pressure,
V_t ; the volume of the total TAH,
V_d ; the volume of the diastolic sac,
V_s ; the volume of the systolic sac,
n ; the amount of filled air,
R ; the ideal gas constant,
T ; the absolute temperature of the interventricular space,
C_w ; the compliance of the membrane,
V_{ivs} ; the interventricular volume.

We can easily calculate the volume of the systolic blood sac since we assume the actuator moves as the given velocity profile indicates. We also acquire the volume of the diastolic blood sac by the integration of the inflow. Therefore, we are able to get the interventricular pressure and volume. The compliance concept relates the interventricular pressure with volume:

$$C_{ivs} = \frac{dV_{ivs}}{dP_{ivs}} = \frac{dV_{ivs}}{dt} \cdot \frac{dt}{dP_{ivs}} \quad (3)$$

The pulmonary circulatory loop and the body circulatory loop are also modeled. For computational efficiency and simplicity, both loops are modeled by cascading lumped-parameter compartments for the various hydraulic compliant elements in the circulation[3-5]. Each hydraulic element is characterized by a set of equations describing the pressure, volume, and flow of the segment, as well as, a set of parameters describing the segment's resistance, inertance, and compliance. Thus, for the ith hydraulic compartment in the circulation, the pressure (P_i), volume (V_i), and flow(Q_i) can be computed as follows:

$$P_{i-1} - P_i = Q_i R_i + L_i \frac{dQ_i}{dt} \quad (4)$$

$$\frac{dV_i}{dt} = Q_i - Q_{i+1} \quad (5)$$

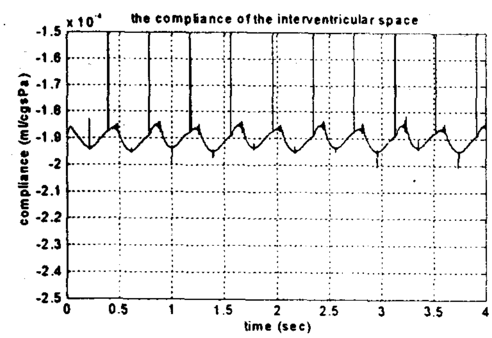
$$P_i = \frac{1}{C_i}(V_i - V_{i,u}) \quad (6)$$

where, $V_{i,u}$; the unstressed volume of ith segment.

The TAH model and the circulatory model are combined to simulate the action of the TAH after implantation.

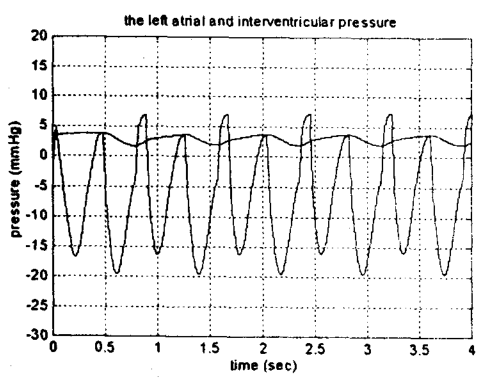
RESULTS

The model is capable of determining the instantaneous compliance of the interventricular space. The compliance values for the fixed amount of air are shown in Fig. 1. It shows some artifacts of tall peaks since the compliance is derived from differentiation.



<Fig. 1> the compliance of the interventricular space

For the verification of the model, the left atrial and interventricular pressure waveforms are acquired and shown in Fig. 2.



<Fig. 2> the left atrial and interventricular pressure waveforms

DISCUSSION

In this study, we have presented a relatively simplified model of the moving-actuator type TAH that is capable of determining the compliance of the interventricular space, i.e., the compliance of the TAH. As expected, the compliance increases in magnitude with filling more air into the interventricular space. The model can also generate realistic waveforms of the aortic and interventricular pressure. Of course, the model should be modified if we want to compute more accurately the compliance of the TAH and other hemodynamic variables. However, this simplified model may be used as an initial step for simulating the performance of the implanted TAH.

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