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Fuzzy Control Method for Balancing Left and Right Cardiac Output in Total Artificial Heart

Insun Shin*, Boyeon Kim, Sanghoon Lee, Jinwook Choi, Byounggoo Min

＝**Abstract**＝

Balancing left/right cardiac output is essential for the automatic control of total artificial hearts(TAH). A fuzzy logic-based control method is presented. We use left atrial pressure(LAP) and right atrial pressure(RAP) as indicators for left/right balancing. The fuzzy controller has four input variables which are measured LAP and RAP and their gradients. Desired variations in left cardiac output(LCO) and right cardiac output(RCO) are calculated to keep LAP and RAP within the Physiological limits. Computer simulations were performed to adjust fuzzy membership functions for variables and verify this control method. Results from simulations showed that LAP and RAP returned to the physiological limits while AoP and PAP stayed within the physiological limits.

1. INTRODUCTION

One of the main requirements for controlling of total artificial heart(TAH) is balancing left and right cardiac output(LCO and RCO) to prevent the faults of blood distribution between pulmonary and systemic circulation. The blood volume in pulmonary circle's reservoir can be expressed as follow :

$$V(t)=V_o+\int_0^t \{q_L(t)-q_R(t)\}dt$$

where q_L and q_R are flows through left and right pumps.

The above expression suggests that the integral kind of accumulation in one of the circulation circle's parts may occur even when the difference in right and left pump flows is small [1]. The right atrial pressure(RAP) and the left atrial pressure(LAP) are used as indicators for the left/right balance. Very low RAP cause collapse the natural atrium and the veins, thereby inhibiting venous return. High RAP impede venous return, cause congestion of the liver and veins, and loss of fluid from the circulatory system. High LAP cause pulmonary

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Dept. of Biomedical Engineering, Institute of Biomedical Engineering*, College of Medicine, Seoul National University
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congestion or edema. Low LAP cause collapse of the atrium and pulmonary veins[2]. Therefore, it is very important to maintain RAP and LAP within the physiological ranges(3-7 mmHg for RAP and 6-12 mmHg for LAP) when TAH is implanted.

Many investigators suggested the automatic control methods for TAH to maintain atrial pressures within physiolosical limits. Henning and its coworkers[3] developed a control system to increase LCO with increasing in aortic pressure(AoP). On the other hand, LCO was decreased in response to increasing in AoP by Pierce and his coworkers[4]. Kitamura, et al. developed a multi-objective control system for artificial heart using an adaptive control strategy. However, they are not widely used in practical operation of TAH due to the intrinsic characteristics of physiological system such as non-linearity, time variation, etc. The absence of a constructive theory of artificial blood circulation make it more difficult to get a reliable control system. Furthermore, it is very difficult to construct a control system with two input and two output variables by using conventional control algorithms. However, our aim is maintaining RAP with 3-7 mmHg and LAP with 6-12 mmHg by regulating RCO and LCO. Conventional control logic is insufficient to represent "fuzzy" information which is common in medical knowledge.

In this paper, we have developed a new method, a fuzzy logic based real time control method for physiological control of TAH. The main advantages of this approach seem to be the possibility of implanting "rule of thumb" experience, intuition, heuristics and the fact that it does not need a model of the system. This method is also efficient in the sense that the target of the control is keeping RAP and LAP within the physiological limits not keeping them some fixed values.

2. METHOD

The schematic diagram of fuzzy LAP and RAP control system is shown in Fig. 2. We have four input variables for the fuzzy controller(fuzzy algorithm). They are

X1(k) = Measured LAP-5mmHg

X2(k) = Measured RAP-9.5mmHg

Y1(k) = X1(K)-X2(k), and

Y2(k) = X2(k)-X1(k).

We have two output variables from the controller. They are variations in left and right cardiac outputs (d_LCO and d_RCO). Each of variables is expressed

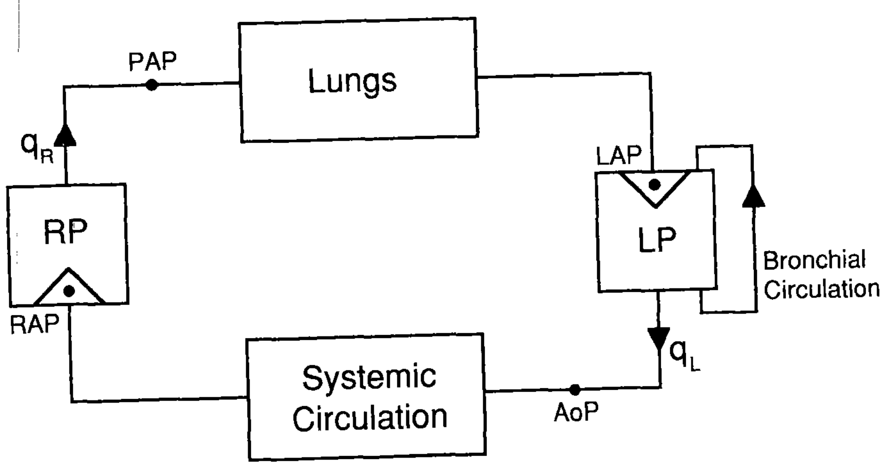


Fig. 1 Schematic diagram of the blood circulation circuit

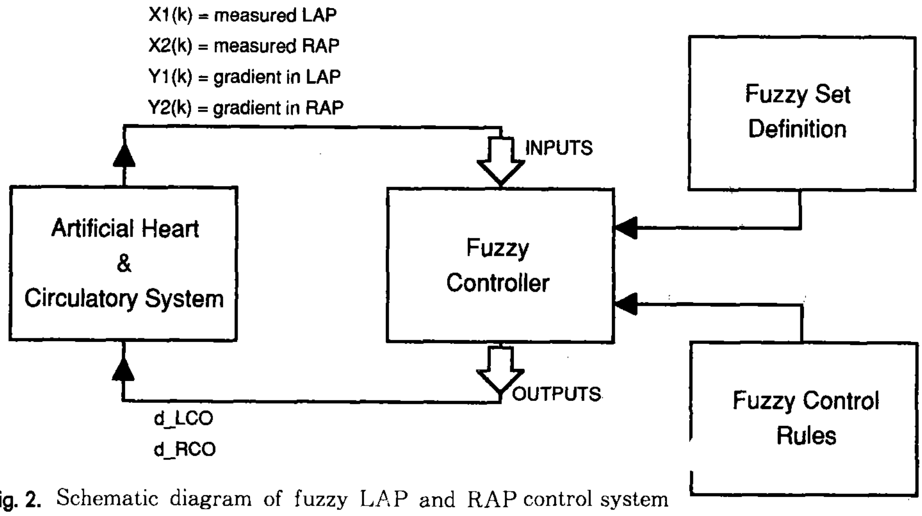


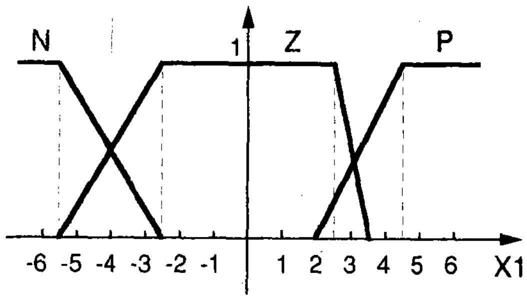
Fig. 2. Schematic diagram of fuzzy LAP and RAP control system

as a fuzzy variable by establishing corresponding membership functions and fuzzy control rules based on the expert's knowledge for control which are shown in Fig. 3 and table 1. If we use n fuzzy subsets for each input variables, there are n^4 cases in look-up table. We used 3 fuzzy subsets for imput variables as follows P is "high", Z is "normal", and N is "low". The grades of memberships for the output variables will normally depend on the ability and the sensitivity of the pump and the system we are considering. In this paper, we assigned them according to the pump of the Korean total artificial heart and the simulated circulatory system using computer model [6]. The applicable fuzzy control rules are retrieved by fuzzy composition rules. The center of gravity method is used for defuzzification (calculation changes in LCO and RCO).

If at least one of two measured pressures is out of the physiological ranges, fuzzy algorithm is applied to calculate desired changes in LCO and/or RCO.

Table 1 Fuzzy Control Rules

	X2	P		P		P		Z		Z		Z		N		N		N	
X1	Y2 / Y1	P		Z		N		P		Z		N		P		Z		N	
P	P	PS	PB	PS	PB	Z	PB	Z	PB	NS	PB	NS	PB	NS	PB	NB	PB	NB	PB
P	Z	PS	PB	PS	PB	PS	PB	Z	PB	Z	PB	NS	PB	NS	PB	NB	PB	NB	PB
P	N	PS	PB	PS	PB	PS	PB	PS	PB	Z	PS	NS	PS	NS	PS	NB	PS	NB	PS
Z	P	PB	PS	PB	PS	PS	PS	PS	PS	Z	PS	NS	Z	NS	PS	NB	PS	NB	Z
Z	Z	PB	PS	PB	Z	PS	Z	PS	Z	Z	Z	NS	Z	NS	Z	NB	Z	NB	NS
Z	N	PB	Z	PB	NS	PS	NS	PS	Z	Z	NS	NS	NS	NS	NS	NB	NS	NB	NS
N	P	PB	NS	PB	NS	PS	NS	PS	NS	Z	NS	NS	NS	NS	NS	NB	NS	NB	NS
N	Z	PB	NB	PB	NB	PS	NB	PS	NB	Z	NB	NS	NB	NS	NB	NB	NB	NB	NB
N	N	PB	NB	PB	NB	PS	NB	PS	NB	Z	NB	NS	NB	NS	NB	NB	NB	NB	NB



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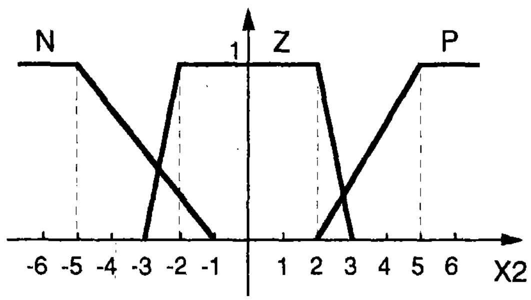

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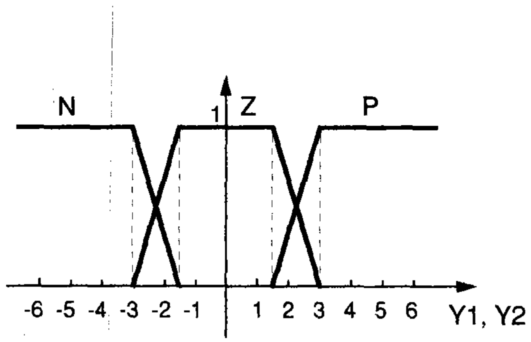

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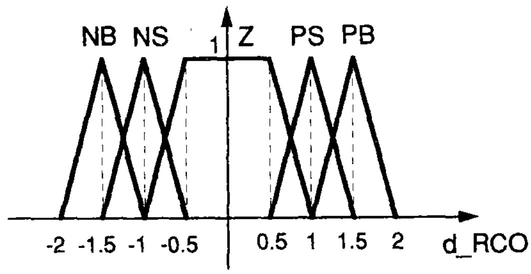

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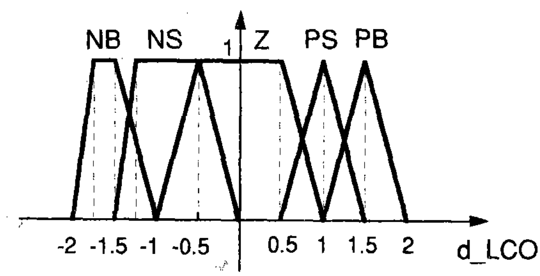


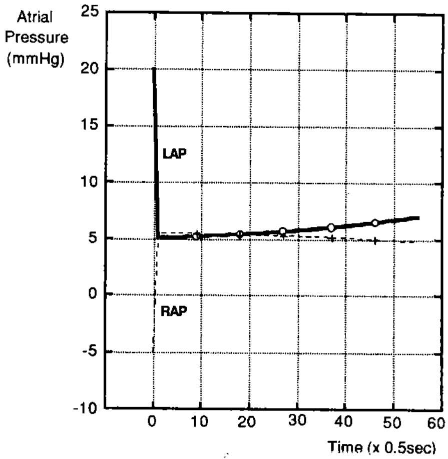
e

Fig. 3 a) Membership function for LAP(X1)
b) 〃 for gradients(Y1, Y2)
c) 〃 for RAP(X2)
d) 〃 for variations in right cardiac output(d_RCO)
e) 〃 for variations in left cardiac output(d_LCO)

3. SIMULATION

To evaluate the present system, simulations by suing computer model based on [6] were performed. We set up the following different conditions ;

a) LAP is normal and RAP is high.
b) LAP is normal and RAP is low.
c) LAP is high and RAP is high.
d) LAP is normal and RAP is normal.
e) LAP is normal and RAP is low.
f) LAP is low and RAP is high.
g) LAP is normal and RAP is hormal.



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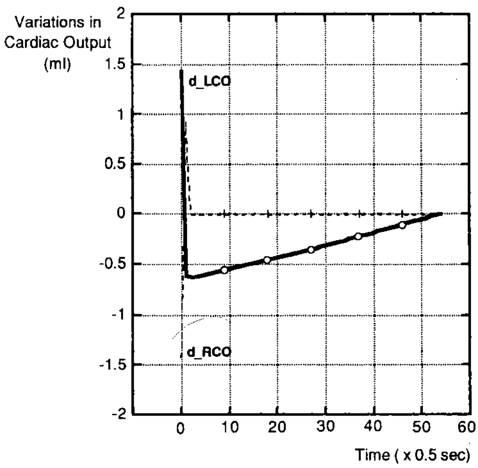

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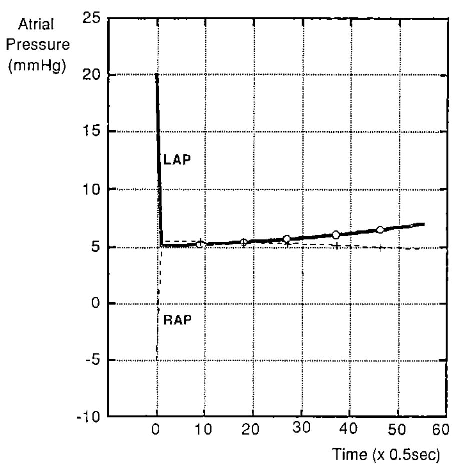

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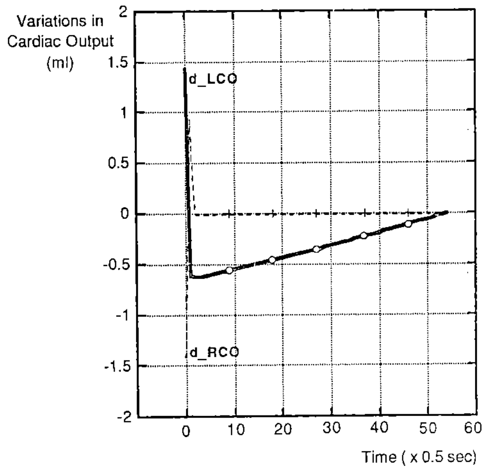

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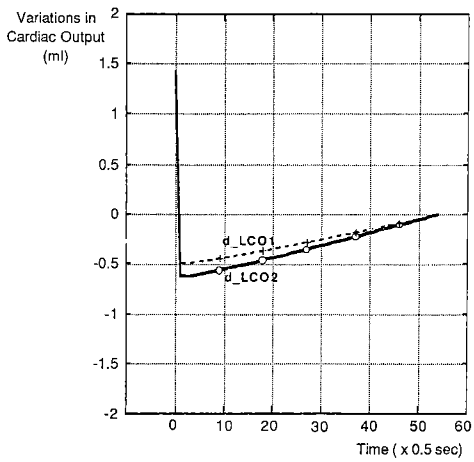

e

Fig. 4 Result of simulation for case with Initial Condition :

LAP=20mmHg, RAP=-5mmHg,
AoP=100mmHg, PAP=15mmHg

a) Changes in LAP and RAP

b) Changes in d_LCO and d_RCO

h) LAP is normal and RAP is low.

The gradients of LAP and RAP were set to zero initially in these simulation. Fig. 5 is and example of the results of simulations for the case e). We could see LAP and RAP returned to the physiological ranges while RAP and AoP stayed in the physiological ranges for all 8 cases.

The membership functions and the fuzzy control rules shown in Fig. 3 may not be fixed. Experts can evaluate their own control strategy and modify it easily by reconstructing membership functions and/or control rules.

For example, we had established a same set of membership functions for variations in LCO and RCO. It was shown that there was a down fall of LAP. Since high LAP is more dangerous than slight low LAP, we changed membership functions in part. NB and NS functions for variations in LCO were modified from Fig. 3 d) to e). Fig. 5 shows the difference in variations in LCO corresponding to the two different sets of output membership functions.

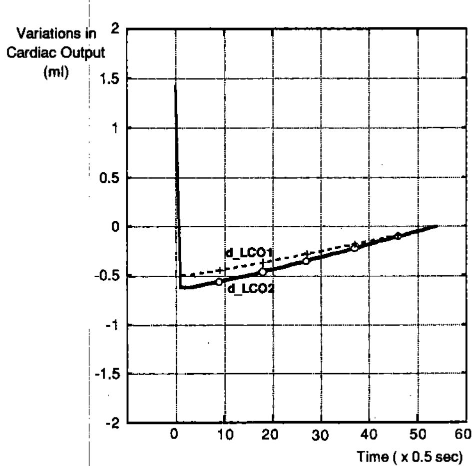

Fig. 5 Comparison of d LCO corresponding to the two different sets of output membership functions, where d LCO1 and d LCO2 corresponds to Fig.3 d) and e) respectively.

4. DISCUSSION

Effectiveness of fuzzy control method strongly depends on constructing proper membership functions and control rules. On the other hand, the distinction of fuzzy control method comes from the facts that it is easy to analyze and modify membership functions and control rules. So that expert's knowledge can be reflected directly.

This work is the first step for fuzzy control method for balancing LCO and RCO in TAH. Accumulated knowledge from animal experiments will enhance reliability of this method.

The eventual goal of this work is to design an automatic controller for TAH. If we consider a long term implantation, we need to vary the cardiac output in accordance with changes in the body's demands for blood-supplied substances. It can be done by constructing several sets of membership functions and selecting one of them according to a change of body posture and a certain degree of body activity etc.

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