What is optimal cardiopulmonary resuscitation technique for children?

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ABSTRACT

We present optimal cardiopulmonary resuscitation (CPR) technique based on body weight using optimal control theory. The validated blood circulation model of CPR has been modified for various body weights by the scaling law. The external chest and abdomen pressures are chosen as controls and the goal is to maximize the mean systemic perfusion pressure (SPP). The numerical results show that four phases CPR method, such as Lifestick CPR, gives the optimal CPR technique. The most interesting result is that more weighted person needs longer compression duration on the abdomen and less weighted person, like children, needs longer compression duration on the chest.

INTRODUCTION

Is Standard-CPR the best way to survive a patient who suffers a cardiac arrest? Not surprisingly, perhaps, survival rates from sudden cardiac death, treated with lay rescuer or professional rescuer CPR, have remained similarly stable, ranging from 2 to 5 percent for long term survival from out of hospital cardiac arrest in adults, and from 10 to 20 percent for long term survival from in hospital cardiac arrest. Moreover, the American Heart Association and the American Red Cross provide the different standard CPR training and guidelines for infants, children and adults.

The purpose of this research is to develop systematic methodology to improve hemodynamic efficiency of Cardiopulmonary Resuscitation (CPR) techniques for various body weights by applying Optimal Control (OC) on a validated ODE circulation model that was developed by Babbs [1]. As control inputs, we choose the waveform of pressures developed within the chest and the abdomen as functions of time caused by external compression or decompression. Goal is to maximize the mean systemic perfusion pressure (SPP). The numerical results show that four phases CPR method, such as Lifestick CPR, gives the optimal CPR technique. The most interesting result is that more weighted person needs longer compression duration on the abdomen and less weighted person, like children, needs longer compression duration on the chest.
MATHEMATICAL MODEL

The circulation model (Figure 1) describes the adult human circulation (hemodynamics) and consists of seven difference equations, with time as the discrete underlying variable. As control inputs, we choose the patterns of the pressure within the chest and the pressure within the abdomen.

The pressure state variables are as follows:

- P1 pressure in abdominal aorta (AA)
- P2 pressure in inferior vena cava (IVC)
- P3 pressure in carotid arteries (car)
- P4 pressure in jugular veins (jug)
- P5 pressure in thoracic aorta (Ao)
- P6 pressure in right heart and superior vena cava (RH)
- P7 pressure in thoracic pump (i.e. pulmonary vasculature and left heart) (P).

At the step \( n \), when the elapsed time is \( n \Delta t \), the pressure vector is denoted by:

\[
P(n) = (P1(n); P2(n); \ldots; P7(n)).
\]

![Figure 1. Circulation diagram corresponding to the model](image)

We use two controls, the first one acting on the chest and the second one acting on the abdomen. We assume that the admissible controls are equal at the beginning and the end of the time interval, i.e., \( u_1(0) = u_1(N-1) \) for \( i = 1; 2 \). Using the two control vectors, \( u_1 = (u1(0), u1(1), \ldots, u1(N-2), u1(0)) \) and \( u_2 = (u2(0), u2(1), \ldots, u2(N-2), u2(0)) \), the difference equations (in vector notation) representing the circulation model read as follows:

\[
P(1) = P(0) + T1(u1(0)) + T2(u2(0)) + \Delta t F(P(0))
\]

\[
P(n+1) = P(n) + T1(u1(n) - u1(n-1)) + T2(u2(n) - u2(n-1)) + \Delta t F(P(n)), \ n = 1, 2, \ldots, N-1,
\]

where \( T1 \) and \( T2 \) represent the linear maps as follows:
Here, we define the function $F(P(n))$ by listing its seven components in terms of pressures, compliances, and resistances as shown in Figure 1 and in Babbs’ work [1]. For detailed description for the equations, see the previous works in [2, 3, 4].

The compliances and resistances are now changed for various body weights by scaling law. Our objective functional is

$$J(u_1, u_2) = \sum_{n=1}^{N} [P_5(n) - P_6(n)] - \sum_{n=0}^{N-2} \left[ \frac{B_1}{2} u_1^2(n) + \frac{B_2}{2} u_2^2(n) \right],$$

And our goal is to maximize $J(u_1, u_2)$.

### NUMERICAL RESULTS

In this section, optimal CPR technique based on body weight has been investigated numerically. The optimal control theory developed in [1] has been applied to the model and the following iterative method is used to find the optimal controls, which are optimal external chest and abdomen pressures. We consider the weights, 8, 16, 32, 64 and 128kg and the upper and lower bounds are -20mmHg and 60mmHg for the chest and -20mmHg and 120mmHg for the abdomen, respectively.

Figure 2 shows the period (o) and the compression duration for chest (*) as functions of weight. From this results, more weighted person needs longer compression duration on the abdomen and less weighted person, like children, needs longer compression duration on the chest.

![Figure 2](image_url)
REFERENCES