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Optimum Compression to Ventilation Ratios in Cardiopulmonary Resuscitation: A Simulation Study

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Abstract

Goal: The purpose of this paper is to investigate optimum compression to ventilation ratios in Cardiopulmonary Resuscitation (CPR). Methods: Mathematical modeling approach is used. Equations describing oxygen, carbon dioxide exchange and blood flow as functions of the compression to ventilation ratio during CPR are developed. The model is validated against normal physiology and animal studies of CPR. Then the model equations are solved to find the optimum compression to ventilation ratios for both professional and lay rescuers. As rescuer performance might vary greatly, Monte Carlo simulations with parameters of rescuer performance randomly chosen are performed to examine whether the optimum compression to ventilation ratios achieved above fit most cases. Results: Results show that the optimum compression to ventilation ratio is around 50:2 for professional rescuers, and is round 70:2 for lay rescuers. Conclusion: The 30:2 compression to ventilation ratio, which is specified in International Guideline, might not be optimum for professional rescuers, might be even worse for lay rescuers. It suggests the 50:2 and 70:2 compression to ventilation ratios might be optimum for professional and lay rescuers respectively. Significance: The 50:2 and 70:2 compression to ventilation ratios might maximize optimum oxygen delivery to body tissue during CPR, and thus lead to better survival rates.

Keywords: Optimum Compression to Ventilation Ratios; Cardiopulmonary Resuscitation; Monte Carlo Simulations; Mathematical Modeling;

1 Introduction

Cardiopulmonary Resuscitation (CPR) is a medical treatment taken to rescue cardiac arrest patients. The quality of CPR delivered has an important impact on success rates [1]. CPR includes chest compressions and ventilations, with chest compression to generate forward blood flow, and with ventilations to deliver oxygen to body tissue.

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Current International Guideline [2] recommends a compression to ventilation ratio of 30:2. That is, the rescuer compresses the chest 30 times, pauses to give 2 mouth-to-mouth ventilations, and then continues with chest compressions. But there is no evidence supporting or refuting whether 30:2 is the optimum compression to ventilation ratio.

Suppose chest compressions are performed at a compression rate of 100/min as recommended in current International Guideline [2]. If a rescuer takes 5 s to deliver 2 mouth-to-mouth ventilations, then with a 30:2 ratio, chest compressions are delivered 78% of the time. In real world, a rescuer may need much longer time, say 16 s to deliver 2 mouth-to-mouth ventilations [3], with a 30:2 ratio, chest compressions are only delivered 53% of the time.

When giving ventilations, chest compressions are interrupted, the forward blood flow generated during chest compression will gradually fall to zero, which has a detrimental effect to oxygen delivery.

Some researchers experiment on other compression to ventilation ratios such as 100:5, 60:2, 100:2 and etc, to see whether they will provide better CPR quality. Kill et al. [4] compare effects of compression to ventilation ratios of 30:2, 100:5, 100:2 and compression only CPR with pig models. Their results find that 100:5 is basically equivalent to 30:2, while 100:2 and compression only CPR reduces the chance of resuscitation success rate. Sanders et al. [5] compare effects of compression to ventilation ratios of 15:2, 50:5, 100:2 and compression only CPR with pig models. Their results find that 100:2 group achieves the best outcome. There are many confounding factors existing in clinical and animal studies, which make these studies hard to repeat, produce conflicting results.

Some studies use mathematical modeling approach to find the optimum compression to ventilation ratio. Tuner et al. [6, 7] show that a compression to ventilation ratio around 20:1 might provide the best resuscitation effects. Babbs et al. [3] show that for professional rescuers, the optimum compression to ventilation ratio is around 30:2, whilst for lay rescuers (who take much longer time to administer rescue breaths than professional rescuers), the optimum ratio is around 60:2.

This paper takes a mathematical modeling approach, equations describing oxygen and carbon dioxide delivery to body tissues and blood flow as functions of the compression to ventilation ratio during CPR are developed. Then the optimum compression to ventilation ratio is calculated after solving the model equations. Since rescuer performance may vary greatly, Monte Carlo simulations were also performed to find the optimum compression to ventilation ratio with varying rescuer performance.

2 Method

2.1 Approach

Glossary of symbols is listed in Table 1.

The lung is treated as a single gas exchange compartment with a 150 ml dead space volume. Rescuer breath with oxygen concentration F_IO_2 and carbon dioxide concentration F_ICO_2 is administered to the lung during CPR. The amount of air administered is determined according to International Guideline. The respiratory rate R, i.e., frequency of ventilations in one minute, is calculated for each compression to ventilation ratio, thus allowing the amount of air administered each minute to be calculated.

Table 1: Glossary of symbols

Variable	Definition	Value	Units
$f_{I,\mathrm{O_2}}$	Fraction of oxygen in inspired gas exhaled by rescuer during one-rescuer CPR	0.17	–
$f_{I,\mathrm{CO_2}}$	Fraction of carbon dioxide in inspired gas exhaled by rescuer during one-rescuer CPR	0.04	–
$f_{A,\mathrm{O_2}}$	Fraction of oxygen in alveolar gas	–	–
$f_{A,\mathrm{CO_2}}$	Fraction of carbon dioxide in alveolar gas	–	–
n_1	Number of compressions per complete compression/ventilation cycle	–	–
n_2	Number of ventilations per complete compression/ventilation cycle	–	–
x	Compression/ventilation ratio, i.e. n_1/n_2	–	–
Q_{MAX}	Maximum forward blood flow during continuous chest compressions	1000	ml/min
$\bar{Q}$	Mean forward blood flow including ventilator pauses	–	ml/min
s	Pulmonary shunt fraction	0.024	–
$P_{A,\mathrm{O_2}}$	Partial pressure of oxygen in alveolar gas	–	mmHg
$P_{A,\mathrm{CO_2}}$	Partial pressure of Carbon dioxide in alveolar gas	–	mmHg
$P_{a,\mathrm{O_2}}$	Partial pressure of oxygen in arterial blood	–	mmHg
$P_{a,\mathrm{CO_2}}$	Partial pressure of carbon dioxide in arterial blood	–	mmHg
$P_{v,\mathrm{O_2}}$	Partial pressure of oxygen in venous blood	–	mmHg
$P_{v,\mathrm{CO_2}}$	Partial pressure of carbon dioxide in venous blood	–	mmHg
$C_{Ae,\mathrm{O_2}}$	Concentration of oxygen in pulmonary end-capillary blood	–	ml (STPD)/ml
$C_{Ae,\mathrm{CO_2}}$	Concentration of carbon dioxide in pulmonary end-capillary blood	–	ml (STPD)/ml
$C_{a,\mathrm{O_2}}$	Concentration of oxygen in arterial blood	–	ml (STPD)/ml
$C_{a,\mathrm{CO_2}}$	Concentration of carbon dioxide in arterial blood	–	ml (STPD)/ml
$C_{v,\mathrm{O_2}}$	Concentration of oxygen in venous blood	–	ml (STPD)/ml
$C_{v,\mathrm{CO_2}}$	Concentration of carbon dioxide in venous blood	–	ml (STPD)/ml
K_1	Constant for the oxygen dissociation curve	0.2	ml (STPD)/ml
K_2	Constant for the oxygen dissociation curve	0.046	mmHg^{-1}
$K_{\mathrm{CO_2}}$	Slope of the carbon dioxide dissociation curve	0.0065	ml (STPD)/(ml·mmHg)
$k_{\mathrm{CO_2}}$	Constant for the carbon dioxide dissociation curve	0.244	ml (STPD)/ml
t	Time spent for one chest compression/relaxation in CPR	0.01	min
T	Average time spent for one ventilation in CPR	0.042	min
R	Average rate of ventilations in CPR	–	min^{-1}
v_T	Tidal volume	700	ml (BTPS)
v_D	Dead space volume	150	ml (BTPS)
$\dot{V}_{O_2}$	Oxygen delivery to body tissue	–	ml (STPD)/min
$\dot{V}_{CO_2}$	Carbon dioxide produced by body tissue	–	ml (STPD)/min
k	Factor converting from STPD to BTPS conditions	1.21	–

STPD, Standard Temperature and Pressure, Dry. BTPS, Body Temperature and Pressure, Saturated.

Mean blood flow Q will be calculated for different compression to ventilation ratios from $Q_{\max}$, which is the maximum blood flow that will be generated without ventilatory pause. Venous blood gets oxygenated when it goes through the pulmonary capillaries. Pulmonary shunt fraction s is taken into account here, i.e., part of venous blood goes directly to arterial vessels without getting oxygenated. So in the model diagram, blood flow Q_s won't get oxygenated, while blood flow $Q(1-s)$ will go through the pulmonary capillaries and get oxygenated. When arterial blood goes through body tissue, oxygen will be consumed and carbon dioxide will be produced.

As how much oxygen will be consumed during CPR is unknown, the partial pressure of oxygen in venous blood P_vO_2 is assumed to be an unchanged 20 mmHg, which is consistent with the experimental studies. These studies record that whether the compression to ventilation is 30:2 or 15:2, P_vO_2 is around 20 mmHg [8, 9].

2.2 Equations

A set of equations describing oxygen, carbon dioxide delivery to body tissue, and blood flow during CPR are developed.

In balance, the mass balance equation for oxygen is as follows:

$$(v_T - v_D)Rf_{I,\mathrm{O}_2} = (v_T - v_D)Rf_{A,\mathrm{O}_2} + k\bar{Q}(C_{a,\mathrm{O}_2} - C_{v,\mathrm{O}_2}) \tag{1}$$

The left-hand term is oxygen flow into the lung, the right hand term is oxygen flow out of the lung plus the oxygen delivered to body tissue. In the above equation, k is the factor converting from STPD to BTPS conditions, R is the average rate of ventilations in CPR, Q is the mean forward blood flow including ventilator pauses.

Average rate of ventilations R can be expressed as a function of compression to ventilation ratio $n_1 : n_2$, time spent for one chest compression/relaxation t, and average time spent for one ventilation T [3].

$$R = \frac{n_2}{n_2T + n_1t} = \frac{1}{T + xt} \tag{2}$$

When the chest is being compressed, it is assumed that forward blood flow will linearly rise from 0 to maximum forward blood flow Q_{MAX}. When breaths are administered, the forward blood flow will linearly fall from Q_{MAX} to 0. And it is assumed that the rise time and down time is equal [3]. With these assumptions, mean blood flow can be expressed as follows:

$$Q = Q_{MAX}\frac{n_1t}{n_2T + n_1t} = Q_{MAX}\frac{X}{T/t + X} \tag{3}$$

Concentration of oxygen in arterial blood C_{a,O_2} can be expressed by concentration of oxygen in pulmonary end-capillary blood and venous blood:

$$C_{a,\mathrm{O}_2} = (1 - s)\, C_{Ae,\mathrm{O}_2} + sC_{v,\mathrm{O}_2} \tag{4}$$

Here s is pulmonary shunt fraction.

The dissociation relation for oxgyen in both arterial and venous blood is as follows [10]:

$$C_{\mathrm{O}_2} = K_1 \left(1 - e^{-K_2P_{\mathrm{O}_2}}\right)^2 \tag{5}$$

In the above equation K_1 and K_2 are constants for oxygen dissociation curve, C_{O_2} is concentration of oxygen in arterial or venous blood, P_{O_2} is partial pressure of oxygen in arterial or venous blood.

In order to calculate C_{Ae,O_2}, it is assumed that in equilibrium, partial pressure of oxygen in pulmonary end-capillary P_{Ae,O_2} equals partial pressure of oxygen in alveolar gas P_{A,O_2}. And P_{A,O_2} can be calculated from f_{A,O_2}:

$$P_{A,\mathrm{O}_2} = 713f_{A,\mathrm{O}_2} \tag{6}$$

Here 713 is atmospheric pressure 760 mmHg minus the water vapor pressure 47 mmHg.

The optimum compression to ventilation ratio is the ratio that maximizes oxygen delivery to body tissue. Oxygen delivery to body tissue $\dot{V}_{O_2}$ is defined as follows:

$$\dot{V}_{O_2} = Q(C_{a,O_2} - C_{v,O_2}) \tag{7}$$

Carbon dioxide production $\dot{V}_{CO_2}$ in CPR is assumed to be proportional to oxygen consumption $\dot{V}_{O_2}$ as in normal physiology:

$$\dot{V}_{CO_2} = 0.8\dot{V}_{O_2} \tag{8}$$

And also $\dot{V}_{CO_2}$ can be expressed in terms of concentrations of carbon dioxide in arterial and venous blood:

$$\dot{V}_{CO_2} = \bar{Q}(C_{v,CO_2} - C_{a,CO_2}) \tag{9}$$

Similar to Eq. (1), in balance, mass balance equation for carbon dioxide can be described as follows:

$$(v_T - v_D)Rf_{I,CO_2} + k\bar{Q}(C_{v,CO_2} - C_{a,CO_2}) = (v_T - v_D)Rf_{A,CO_2} \tag{10}$$

In the above equation, the left-hand term is carbon dioxide flow into the lung plus carbon dioxide produced by body tissue, the right-hand term is carbon dioxide flow out of the lung.

Similar to Eq. (4), concentration of carbon dioxide in arterial blood can be expressed as follows:

$$C_{a,CO_2} = (1 - s)\, C_{Ae,CO_2} + sC_{v,CO_2} \tag{11}$$

The dissociation relationship for carbon dioxide in both arterial and venous blood is as follows [10]:

$$C_{CO_2} = K_{CO_2}P_{CO_2} + k_{CO_2} \tag{12}$$

In the above equation, K_{CO_2} is the slope of the carbon dioxide dissociation curve, k_{CO_2} is a constant for carbon dioxide dissociation curve.

2.3 Computational Aspects

For each different compression to ventilation ratio, Eqs. (2)-(6) will be plugged in to Eq. (1), leaving only f_AO_2 as a variable. Then f_AO_2 will be solved using Newton's method. After solving f_AO_2, other values that are of interests can be easily calculated using Eqs. (2)-(9).

3 Results

First the model was validated by comparing simulation results with normal physiology. In order to adpat the model to simulate normal physiology, oxygen partial pressure in venous blood P_vO_2 was set as 40 mmHg, R in this case means respiratory rate and was set as 13, Q in this case means cardiac output and was set as 5000 ml/min, v_T in this case means tidal volume and was set as 500 ml (STPD), f_{I,O_2} and f_{I,CO_2} in this case means concentration of oxygen and carbon dioxide in air and was set as 0.21 and 0 respectively. These values were all set according to parameters of normal physiology [11]. With these adaptions, Eqs. (1) and (4)-(12) can be used to describe gas exchange in normal physiology. After these setups, other parameters of normal physiology can be easily calculated: P_AO_2 = 99 mmHg, P_aO_2 = 93 mmHg, P_ACO_2 = 40 mmHg, P_aCO_2 = 40 mmHg, P_vCO_2 = 47 mmHg. $\dot{V}_{O_2}$ = 265 mL (STPD)/min, $\dot{V}_{CO_2}$ = 212 mL (STPD)/min. These values are consistent with normal physiology, which were: P_AO_2 = 100 mmHg, P_ACO_2 = 40 mmHg, P_aO_2 = 90 mmHg, P_aCO_2 = 40 mmHg, P_vCO_2 = 46 mmHg, $\dot{V}_{O_2}$ = 260 mL (STPD)/min, $\dot{V}_{CO_2}$ = 0.21 mL (STPD)/min [11].

Then the model was validated by comparing simulation results with animal studies of CPR. For the compression to ventilation ratio of 30:2, the animal study [9] gives P_aO_2 = 48.75 mmHg, P_aCO_2 = 57 mmHg, P_vO_2 = 21 mmHg and P_vCO_2 = 69 mmHg after 3 minutes of CPR. Our simulation study of 30:2 CPR gives P_aO_2 = 84 mmHg, P_aCO_2 = 51 mmHg, P_vO_2 = 20 mmHg and P_vCO_2 = 66 mmHg. Before comparing results of animal study and simulation study, it's important to note that the animal study uses pig models. Baseline P_aCO_2, P_vO_2 and P_vCO_2 are similar for both pigs and humans, while baseline P_aO_2 is quite different for pigs and human. For pigs, baseline P_aO_2 is around 84 mmHg, P_aCO_2 is around 41 mmHg, P_vO_2 is around 40 mmHg, and P_vCO_2 is around 46 mmHg [8]. For humans, baseline P_aO_2 is around 100 mmHg, P_aCO_2 is around 40 mmHg, P_vO_2 is around 40 mmHg, and P_vCO_2 is around 46 mmHg [11]. With similarities and difference of pigs and humans in mind, it's easy to check that simulation results agree well with the animal study.

After validating the model, each compression to ventilation ratio, within the range of 1 to 50, in increment of 1, was chosen, and model equations were solved for this ratio, then oxygen delivery with this ratio was calculated.

Fig. 1 depicts oxygen delivery for each different compression to ventilation ratio. From Fig. 1, it's easy to see that the optimum compression to ventilation ratio is around 20:1 to 30:1 or 40:2 to 60:2 the maximum oxygen delivery is achieved at compression to ventilation ratio of 24:1.

In real world, rescuers may need much longer time, say 16 s instead of 5 s to give two ventilations [3]. For this case, average time for one ventilation T was set as 8 s or 0.133 min. Fig. 2 depicts results for this case. The optimum compression to ventilation ratio is around 30:1 to 35:1 or 60:2 to 70:2, the maximum oxygen delivery is achieved at compression to ventilation ratio of 33:1.

In real world, rescuers' performance may deviate from normal levels, for example, Q_{MAX}

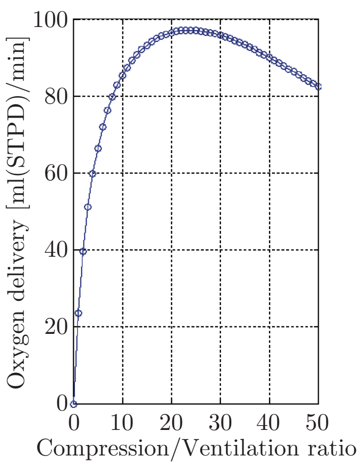

Fig. 1: Oxygen delivery calculated with different compression to ventilation ratios for professional rescuers

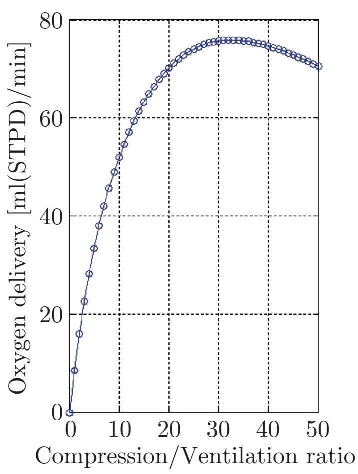

Fig. 2: Oxygen delivery calculated with different compression to ventilation ratios for lay resuers

achieved during CPR might be different from 1000 mL/min, tidal volume administered might be different from 700 mL too. It's easy to see that, for different rescuers, the optimum compression to ventilation ratio might be different.

In order to examine whether the optimum ventilation ratios that were achieved above fit most cases, Monte Carlo simulations as described in [3] were performed with some modifications. In this paper, parameters Q_{MAX}, V_T, T and t are not fixed, but will get random values within certain ranges as specified in Table 2.

Table 2: Statistical parameters for monte carlo simulations

Parameter	Range	Units
Q_{MAX}	800–1200	ml/min
V_T	600–800	ml (STPD)
T	0.032–0.052, ideal 0.123–0.143, practical case	min
t	0.009–0.011	min

Note that there are two different ranges for T, one is for ideal case, which corresponds to professional rescuers who need only 5 s to administer two breaths, the other one is for practical case, which corresponds to lay rescuers who need 16 s to administer two breaths. Simulations were performed 10000 times for each case. During each simulation, Q_{MAX}, V_T, T and t will randomly get uniformly distributed values within ranges as specified in Table 2, all other parameters' values are fixed as specified in Table 1. The optimum compression to ventilation ratio for this parameter set was calculated. After finishing 10000 simulations, the frequency of different optimum compression to ventilation ratio was counted. Results are shown in Figs. 3 and 4.

Fig. 3 is a histogram of the Monte Carlo simulation for 10000 simulated resuscitations, using ideal, guideline, values for ventilation time. From Fig. 3, it's easy to see that most optimum compression to ventilation ratios are in the range of 20–30, which translate to 40:2 to 60:2 compression ventilation ratios, which are in agreement with our previous results.

Fig. 4 is a histogram of the Monte Carlo simulation for 10000 simulated resuscitations, using practical values for ventilation time. From Fig. 4, it's easy to see that most optimum compression to ventilation ratios are in the range 30–35, which translate to 60:2 to 70:2 compression ventilation ratios, which are in agreement with our previous results too.

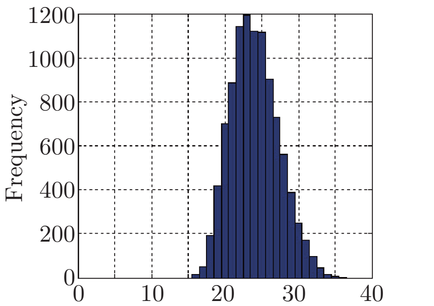

Fig. 3: Histograms of optimal values of compression to ventilation ratio for 10000 simulations. Ideal case

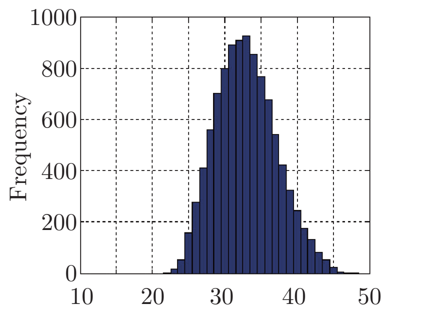

Fig. 4: Histograms of optimal values of compression to ventilation ratio for 10000 simulations. Practical case

4 Conclusion

In this paper, a mathematical model describing oxygen, carbon dioxide exchange and blood flow during CPR was developed. The model was validated against normal physiology and animal study. Then simulations of oxygen delivery for different compression to ventilation ratios were performed using this model. Results show that when CPR was performed according to CPR guideline, the optimum compression to ventilation ratio is around 50:2. And in real world, it takes much longer time to perform two rescue breaths. In this case, the optimum compression to ventilation ratio is around 70:2. As rescuers' performance might vary greatly, Monte Carlo simulations were also performed. The results are in agreement with the above results, which confirm that 50:2 and 70:2 might be the optimum compression to ventilation ratios with ideal and practical rescuer performance respectively.

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