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Abstract

Objective: To develop and evaluate a practical formula for the optimum ratio of compressions to ventilations in CPR. The optimum value of a parameter is that for which a desired result is maximized. Here the desired result is assumed to be either oxygen delivery to peripheral tissues or a combination of oxygen delivery and waste product removal.

Method: Equations describing oxygen delivery and blood flow during CPR as functions of the number of compressions and the number of ventilations delivered over time were developed from principles of classical physiology. These equations were solved explicitly in terms of the compression/ventilation ratio and evaluated for a wide range of conditions using Monte Carlo simulations.

Results: As the compression to ventilation ratio was increased from zero to 50 or more, both oxygen delivery and the combination of oxygen delivery with blood flow increased to maximum values and then gradually declined. For parameters typical of standard CPR as taught and specified in international guidelines, maximum values occurred at compression/ventilation ratios near 30:2. For parameters typical of actual lay rescuer performance in the field, maximal values occurred at compression/ventilation ratios near 60:2

Conclusion: Current guidelines overestimate the need for ventilation during standard CPR by two to four-fold. Blood flow and oxygen delivery to the periphery can be

improved by eliminating interruptions of chest compression for these unnecessary ventilations.

Key words: Cardiopulmonary resuscitation (CPR); Coronary perfusion pressure; Guidelines; Heart arrest; Mouth-to-mouth; Tidal volume

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1. Introduction

Current adult CPR by one or two rescuers is based on the traditional ABC's – airway, breathing, circulation – with a 15:2 compression/ventilation ratio[1]. That is, the rescuer compresses the chest 15 times, pauses to give two mouth-to-mouth ventilations, and then continues with chest compressions[*]. The 15:2 ratio is essentially the same as the normal ratio of heart rate to breathing in a quietly resting adult with a heart rate of 75 beats/min and a respiratory rate of 10 breaths/min, namely 7.5:1 or 15:2. Recently, the issue of the most desirable compression/ventilation ratio has been reopened because of the reluctance of many rescuers, both lay and professional, to perform mouth-to-mouth rescue breathing, owing to the fear of contracting serious communicable diseases such as AIDS[2-4]. Moreover, the relatively long pauses in chest compression required for ventilation lead to disturbingly long interruptions in chest compressions and associated blood flow. In turn, the average systemic perfusion pressure over a complete compression/ventilation cycle may be much lower than is generally appreciated.

Consider, for example, a set of 15 compressions at a compression rate of 100 per minute[1], which requires 9 seconds to deliver. If a rescuer takes 5 seconds to administer two slow, deep rescue breaths of 700 to 1000 ml each, as specified in current Guidelines[1], then chest compressions are only being delivered 9/14ths of the time. The 5-second pause for ventilation following every 15 chest compressions has been shown in experimental models to reduce coronary perfusion pressure by 50% [5]. This loss of perfusion pressure must be rebuilt during each subsequent set of compressions, and typically requires about 5 to 10 compressions before the previous level is achieved[5]. In some cases the 5-second pause for ventilation may reduce overall mean systemic perfusion below the value of approximately 25 mmHg required for effective resuscitation[6-8].

Furthermore, actual observations of lay rescuers suggest that the pause in chest compression required to deliver two ventilations is rarely as brief as 5 seconds. Recent videotape analysis of lay rescuers in action shows that the interruption of chest compression for rescue breathing consistently requires about 16 seconds to perform[9, 10]. The act of delivering two slow, deep rescue breaths is not just the blowing into the mouth of the victim, but the physical task of stopping compressions, leaving the chest, moving to the head, performing a head tilt/chin lift maneuver to open the airway, taking in a breath, bending over, getting a good mouth to mouth seal, blowing in the breath, rising up, taking in a second breath, bending over again, recreating a good seal, blowing in the second breath, watching the chest rise, leaving the head and returning to the chest, finding the proper hand position, and finally beginning to compress the chest again! This

[*] The former convention of 5:1 compression ventilation ratio for two-rescuer CPR has been dropped in the most recent Guidelines for the sake of simplification and coordination between North American and

kinesthetically complex set of tasks is much more difficult for the once trained, but unpracticed, rescuer than is the rhythmic repetition of chest compression.

Hence in a practical, real world setting, with a compression rate of 100/min (the new value specified in the year 2000 international guidelines[1]), chest compressions would be interrupted for ventilations a majority of the time (9 seconds for 15 compressions, 16 seconds for 2 ventilations). In this case chest compressions would be delivered during only 36 percent of the total resuscitation time.

Accordingly, a movement has begun to explore the use of other compression to ventilation ratios such as 50:5[9-12], during which chest compressions are sustained for a greater proportion of the time. The ultimate extension of this concept of increasing the number of chest compressions between ventilation ventilations is "continuous chest compression CPR" without any ventilations. Such a strategy has been extensively studied in a swine model of resuscitation and has shown identical outcome results to standard 15:2 compression to ventilation CPR[11-17]. Recently, Hallstrom et al[18] have reported a clinical study of simplified, dispatcher assisted CPR, in which no ventilations are given. In this study, the results of CPR without ventilations were no worse than those of standard CPR. Such research begs the question as to how much, if any, ventilation is needed in the early treatment of cardiac arrest[16, 19]—or more generally—what is the optimum compression to ventilation ratio?

European practice.

The optimum value of a parameter is that for which a desired result is maximized. Hence the optimum compression to ventilation ratio depends on the particular principle or criterion one chooses to define "desired result". One such principle is that the main purpose of the circulation is to deliver oxygen to peripheral tissues. An extension of this principle is that the purpose of the circulation is not only to deliver oxygen but also to remove metabolic waste products. That is, there may be some independent benefit of circulation even if little or no oxygen is delivered, for example, to clear lactic acid made during prior ischemia and anaerobic metabolism. In this case the function of effectiveness of the circulation can be viewed as the product of some function of blood flow multiplied by some function of oxygen delivery.

The present paper takes a mathematical and physiological approach to finding the optimum compression/ventilation ratio in CPR, where the optimum is defined either in terms of oxygen delivery alone or as a combination of oxygen delivery and perfusion. The results show that 15:2 is optimal for less than 1 percent of patients resuscitated with ideal ventilation technique and virtually none of the patients resuscitated with average ventilation technique characteristic of lay rescuers.

2. Methods and Results

2.1. Approach

To define an optimum value of a parameter, x, one has to plot a desired result as a function of x, and then find the value of x at which the desired result is maximized. Suppose, for example, that the desired result is oxygen delivery. According to the Fick principle, oxygen delivery is equal to cardiac output (forward blood flow) multiplied by the arteriovenous difference in oxygen content (A-V O_2 difference). In this case it is necessary to express blood flow and A-V O_2 difference during CPR as a function, F(x), of the compression ventilation ratio, x, and to find the value of x for maximum oxygen delivery. If F(x) is well behaved, it is also possible also to use calculus to find a general formula for the optimum value, x*, that gives maximal oxygen delivery. In the following analysis we shall examine mathematically how blood flow and oxygen delivery change as a function of the compression to ventilation ratio. For simplicity, we explored only compression to ventilation ratios of the form n:2, such as 15:2, 30:2, or 50:2, although other schemes have been suggested[9, 10] and may have merit. The definitions for all variables and their typical values for standard CPR are provided in Table 1.

2.2. Oxygen delivery

Here the term oxygen delivery is used synonymously with oxygen consumption or oxygen uptake. Oxygen uptake in the lungs and delivery to the periphery is $D_{O_2} = \overline{Q} \cdot \Delta c_{O_2}$, where $\overline{Q}$ is the mean forward blood flow during CPR and Δc_{O_2} is the gain in oxygen content of the blood during its transit through the pulmonary capillaries, and in turn, the loss in oxygen content of blood during its transit through the systemic capillaries.

An analytical expression for mean forward flow as a function of the compression/ventilation ratio, x , is derived in Appendix 1. This expression is

$$\overline{Q} = Q_{MAX} \cdot \frac{x}{T/t + x} , \qquad (1)$$

where T is the average time required for one ventilation (the total ventilatory pause divided by 2 for n:2 schemes), and t is the time for one full compression (the inverse of the compression rate).

For example, under ideal conditions of standard CPR, as specified in the Guidelines,

$$\overline{Q} = 1000 \cdot \frac{x}{4.2 + x} \quad \text{(ml of blood/min).} \tag{1a}$$

Here the parameter 4.2, is based on a time of 5 seconds to for delivery of two rescue breaths. If, however, one uses a more practical value of 16 seconds for delivery of two rescue breaths, characteristic of actual lay rescuers, expression (1) becomes

$$\overline{Q} = 1000 \cdot \frac{x}{13 + x} \quad \text{(ml of blood/min).} \tag{1b}$$

An analytical expression for Δc_{O_2} as a function of the compression/ventilation ratio, x , is derived in Appendix 2. This expression is

$$\Delta c_{O_2} \cong \frac{s \cdot (v_T - v_D) \cdot f_I}{(v_T - v_D) + Q_{MAX} \cdot s \cdot t \cdot x} \quad \text{(ml of oxygen/ml of blood),} \tag{2}$$

where s is a constant related to the oxygen-hemoglobin dissociation curve, and other variables are as previously defined (Table 1). This expression is independent of the duration of ventilatory pauses. For example, under ideal conditions of standard CPR,

$$\Delta c_{O_2} = \frac{132}{550 + 15 \cdot x} \quad \left(\frac{\text{ml } O_2}{\text{ml blood}} \right). \tag{2a}$$

Now consider the changes in expressions (1) and (2) as the compression/ventilation ratio, x, is increased over the range from, say, zero to 50. Mean flow, $\overline{Q}$, is a gradually rising function of x. As x becomes substantially greater than T/t in expression (1), the value of $\overline{Q}$ approaches the maximal asymptotic value. This is because with relatively more compressions and fewer ventilations, interruptions of chest compression become a relatively small fraction of total cycle time. The change in blood oxygen content, Δc_{O_2}, is a gradually falling function of x. As x becomes larger in expression (2), the value of Δc_{O_2} begins to diminish. This is because with relatively more compressions and fewer ventilations, alveolar oxygen concentration falls and becomes insufficient to fully charge hemoglobin.

Figure 1 shows the results of multiplying expressions (1) and (2) to obtain oxygen delivery,

$$D_{O_2} = \overline{Q} \cdot \Delta c_{O_2}, \tag{3}$$

as a function of the compression/ventilation ratio. Also shown are relative changes in component functions (1) and (2).

Figure 1(a) is based upon an average ventilation time of 5 sec/2 breaths = 0.042 min/breath. This value describes the ventilatory pause specified in current Guidelines[1]. As the compression/ventilation ratio increases over the range 0 to 50 and interruptions for chest compression for ventilation become less frequent, relative blood flow improves. At the same time relative alveolar oxygen (f_A / f_I) decreases. The actual oxygen delivery, which is related to product of these functions, rises to a maximum and then gradually falls. In the limiting cases in which there are either no compressions (x = 0) or no ventilations ($x \rightarrow \infty$) steady-state oxygen delivery is zero[*]. Maximal oxygen delivery is obtained for values of x between about 10 and 20, corresponding to 20:2 or 40:2 CPR. Here a reasonable value for the optimum is around 15:1 or 30:2.

Figure 1(b) is based upon an average ventilation time of 16 sec/2 breaths = 0.133 min/breath. This value describes the average ventilatory pause in the Cardiff data[9, 10], characteristic of normally trained lay rescuers. As the compression/ventilation ratio increases over the range 0 to 50, blood flow improves and alveolar oxygen decreases, as before. Now, however, maximal values are obtained for values of x between about 15 and 30, corresponding to 30:2 and 60:2 CPR. Here a reasonable value for the optimum is around 25:1 or 50:2. Note that with average lay rescuer technique (16 sec ventilatory pauses) shown in Figure 1(b) the maximal oxygen delivery is only 100 ml oxygen/min,

[*] In non-asphyxial arrest there may be a maximum supply of oxygen in the residual lung volume equal to about 5 liters x 14 percent oxygen = 700 ml of oxygen. At the normal oxygen consumption rate of 250 ml/min this supply would last less than 3 minutes. Hence for more prolonged CPR we are interested in the steady-state solutions shown in Figure 1.

compared with 140 ml oxygen/min with ideal technique shown in Figure 1(a). This is because the longer ventilatory pauses necessarily limit mean blood flow to the periphery.

2.3. Combined flow and oxygen delivery

Now suppose that the desired result of CPR is a function both of blood flow itself and of oxygen delivery. This criterion comes from the biological idea that both removal of waste products and the delivery of oxygen are necessary and important functions of the circulation. In low flow states like CPR there is a tendency toward anaerobic metabolism with lactic acid formation. There may also have been prior ischemia, leading to waste product accumulation. Accordingly, there may be independent benefits to increased flow without increased oxygen delivery (that is increased flow with decreased arterial oxygen saturation and the same oxygen delivery). This idea is in keeping with the reported success of no-ventilation CPR[11-17]. In this case an arbitrary index of the overall benefit of circulation could be calculated as

$$\text{Benefit} \approx \left[\overline{Q}\right]^{\alpha} \cdot \Delta c_{O_2} \tag{4}$$

for some power α, greater than 1, but probably less than, say, 2.

Figure 2 shows the shape of such a benefit function for chest compressions at 100/min using $\alpha = 1.5$. Consider first ideal CPR with ventilatory pauses of 5 sec/2 breaths.

Figure 2(a) shows that the plateau region is a little more prolonged than in Figure 1(a). Maximal benefit occurs for compression ventilation ratios in the range of 12 to 24, which correspond to 24:2 to 48:2. If there is benefit to perfusion without ventilation, the optimal ratio becomes larger. When ventilatory pauses are taken as 16 sec/2 breaths the results in Figure 2(b) are obtained. In this case maximal benefit occurs for compression ventilation ratios in the range of 25 to 40, which corresponds to 50:2 to 80:2.

2.4. Finding the exact optimum for a given patient

Figures 1 and 2 describe the benefit of CPR performed with a maximal blood flow, Q_{MAX}, of 1000 ml/min and a tidal volume of 800 ml per breath. What happens, however, if in the real world a rescuer departs substantially from these nominal levels?

Variation in the optimum compression to ventilation ratio as caused by the variation in rescuer performance can be dealt with statistically. First, let us find an expression for the exact optimum for any particular kind of rescuer performance. Combining expressions (1) and (2) and (4), it is easy to appreciate that in terms of the compression to ventilation ratio, x, expression (4) is a function of the form

$$F(x) = K\left(\frac{x}{a+x}\right)^{\alpha} \frac{1}{1+bx}. \qquad (5)$$

Here the parameters K, a, and b, which depend on other aspects of rescuer performance but do not depend on x, are

$$K = Q_{MAX}^{\alpha}\, s\, f_I, \quad a = T/t, \quad \text{and } b = \frac{Q_{MAX}\, s\, t}{(v_T - v_D)}.$$

For the expression (5) we can find the particular value of the compression/ventilation ratio, x*, that gives the maximum benefit using calculus, as shown in Appendix 3. The result is

$$x^* = \frac{1}{2}\left(a(\alpha - 1) + \sqrt{a^2(\alpha-1)^2 + 4\alpha\frac{a}{b}} \right). \quad (6)$$

If benefit is assumed to equal oxygen delivery, as in Figure 1, $\alpha = 1$, and $x^* = \sqrt{\frac{a}{b}}$. If benefit is assumed to include both flow and oxygen delivery ($\alpha > 1$), then quadratic expression (6) applies.

The optimum compression/ventilation ratio (6) depends only on parameters a, b, and α. Parameter $a = T/t$ depends on the time, T, a rescuer takes to deliver a ventilation and the period, t, of chest compression. Parameter $b = \frac{Q_{MAX}\, s\, t}{(v_T - v_D)}$ depends on how effectively the rescuer performs chest compressions, as described by Q_{MAX} and t, and also how well the rescuer delivers ventilations, described by v_T. The parameter b also depends to a lesser extent on characteristics of the patient, the oxygen carrying capacity of the blood and the anatomic dead space of the large airways. This means that the optimum compression/ventilation ratio will be different for different rescuer—patient pairs and can even vary with time as a given rescuer tires. Having expression (6) in hand, however, one can use statistical techniques to examine the distribution of optimum compression to ventilation ratios under plausible real world circumstances.

2.5. Monte Carlo methods

To explore a good choice of compression to ventilation ratio in the real world, where rescuer performance can vary greatly, one can perform a Monte Carlo simulation. With this method one recognizes that the parameters such as T, t, and C_{MAX} are actually random variables. If we assume that in a particular situation they are chosen independently and at random from statistical sampling distributions with particular means and standard deviations, we can predict and appreciate the spread or distribution of optimal x^* values in actual practice. To do a Monte Carlo simulation one may use a computer to evaluate expression (6) several thousand times, using different randomly selected values each time from realistic distributions of the key parameters.

The means and standard deviations used for key parameters that determine x^* are shown in Table 2. They are intended to represent a realistic range of rescuer performance. For simplicity we assume that the anatomic dead space and oxygen carrying capacity of blood (hematocrit) of adults are normal and unchanging so that the major factors determining the optimal x^* relate to rescuer performance.

A Visual Basic procedure was created to do the Monte Carlo simulation within a Microsoft Excel spreadsheet. Individual random variables, z_i, with a standard normal distribution were created using the inverse standard normal distribution function normsinv(u), where u is a uniformly distributed random number between zero and one. The first four moments of large samples of the resulting values are quite close to the theoretical moments for the standard normal distribution (namely, 0, 1, 0, and 3), confirming that the z_i behave as expected statistically. Particular values of tidal volume, v_T, for each trial, i, was computed as the mean, 800 ml, plus the standard deviation, 200 ml, multiplied by z_i . Thus the tidal volumes ranged from about 400 to 1200 ml, with a mean of 800 ml. In the case of tidal volume, volumes less than the anatomic dead space of 150 ml were not allowed. The variables C_{MAX}, compression rate (1/t), and ventilation time, T, in Table 2 were computed in a similar manner without any restrictions.

The variable α was chosen from a uniform random distribution between 1.00 and 2.00. For $\alpha = 1$, only oxygen delivery is treated as important. For $\alpha = 2$ oxygen delivery to the periphery and flow without oxygen (waste product removal) are treated as equally important. The random selection of α might be viewed a surrogate for varying "down time" or prior ischemia before the onset of CPR. If there has been prolonged ischemia prior to CPR, waste produced removal may be relatively more important. If there has been minimal down time, as in a witnessed cardiac arrest, waste product removal alone may be relatively less important, in which case oxygen delivery may be the most appropriate figure of merit for CPR. Thus by choosing a range of α values, a range of arrest times can be modeled.

Figure 3(a) is a histogram of the results of the Monte Carlo Simulation for 10,000 simulated resuscitations, using ideal, guideline, values for ventilation time. The class interval of the histogram is 2. Bars are centered over the mid-point of each interval. The mean value of the distribution is 18 and the standard deviation is 5. The distribution is slightly skewed. Mid range values of x^* are in the range of 15 to 20, which translates to a 30:2 or 40:2 compression ventilation ratio, over twice current recommendations. Note that over 99 percent of optimum values are greater than 7.5:1 or 15:2.

Figure 3(b) is a similar histogram of the results of the Monte Carlo Simulation for 10,000 simulated resuscitations, using the 16 sec/2 breath ventilation time. The mean value of the distribution is 35 and the standard deviation is 9. Mid range values of x^* are near

35, which translates to a 70:2 compression ventilation ratio, over four times current recommendations. Virtually all values are greater than 7.5:1 or 15:2.

In the histograms of Figure 3 especially low values of x^* are associated with exceedingly poor ventilations. Low values of x^* are also associated with higher flows, that is Q_{MAX} values. This is because with high blood flow, the blood removes oxygen from the lungs more quickly. Thus the extremely low optimal compression ventilation ratios are associated with extremely poor ventilation and extremely good chest compression. This combination is somewhat unlikely, but could occur with a partially obstructed airway. In some such situations excess numbers of ventilations could further obstruct the airway, as in food choking. In other such situations the partial obstruction is due to improper head tilt. Here a focus on a smaller number of high quality rescue breaths rather than a larger number of rushed rescue breaths could well be helpful. Hence a minimum value for the compression to ventilation ratio of 30:2 seems reasonable.

Extremely high optimal compression to ventilation ratios are associated with extremely good ventilation or extremely poor chest compression. This combination, too, is unlikely, but could happen in an individual with a flail chest or other chest wall abnormality, when a particular rescuer is afraid to push adequately hard on the chest for fear of causing harm, or when a child rescuer resuscitates a large heavy adult. In this case very few ventilations are actually needed since little blood is passing through the lungs to be oxygenated. Hence compression to ventilation ratios that are much higher than 30:2 are adequate under these conditions.

Most resuscitations will occur in the mid-range, in which perfusion and ventilation are relatively matched—both above average, or both below average—in keeping with the overall skill of the rescuer. In these more usual cases the optimum compression to ventilation ratio is likely to be in the range of 20:2 to 50:2 for rescuers who ventilate rapidly and well and between 40:2 and 100:2 for less expert rescuers who take more time to deliver rescue breaths.

3. Discussion

Having solved the problem several different ways, it would appear that the optimal number of compressions to be followed by two ventilations is between 30 and 70, or for simplicity, we can say somewhere in the neighborhood of 50, rather than 15. This 50:2 optimum applies to current standard, one- or two-rescuer CPR delivered by typical lay rescuers. In the future the optimal compression/ventilation ratio may be somewhat less than 50:2 when more effective methods using both chest and abdominal compression are employed, because more effective methods have a greater Q_{MAX} term. For example, with interposed abdominal compression CPR the blood flow is about 180 percent of that during standard CPR[20-22]. Accordingly from expression (5) the best compression/ventilation ratio for interposed abdominal compression CPR might be as low as is 20:2 with 90 chest compression per minute, or 15:2 with 70 chest compressions per minute, if ventilatory pauses were kept to guideline values of 5 sec/2 breaths. Thus as future methods of resuscitation are developed, such as 4-phase CPR incorporating compression and decompression of the chest and the abdomen[23, 24], more ventilation will be required to match the improved perfusion. At present, however, 50:2 ventilation is probably adequate for one or two rescuers limited to chest compressions without adjunctive devices or methods.

The subject of asphyxial versus fibrillatory arrest is worthy of comment. In asphyxial arrest, such as in choking or drowning, there is a preceding episode of hypoxia before circulation stops. A key difference is the alveolar gas composition. Increased ventilation, when possible, may be needed initially to clear alveolar CO_2 (or water) that accumulated during asphyxia and to increase the alveolar concentration of oxygen. Such changes in the alveolar gas composition do not happen in fibrillatory arrest. Indeed the opposite changes may occur due to gasping. For asphyxial arrest one needs to attempt several ventilations initially to restore alveolar gas concentrations toward normal, then proceed as before.

What objections could be raised to 50:2? There are several general anti-change objections. It would require changes in teaching materials and the re-training of instructors. It would confuse those familiar with 15:2 and cause conflict if some rescuers trained in the old way had to work at speed and under pressure with other rescuers trained in the new way. If these objections were heeded, however, there would never be improvement in CPR methods, and, in the larger scheme of things, we would still be using 1970 style computer programs--or no computers at all.

Then there is the objection that some rescuers are too feeble to do 50 compressions in a row. However, pilot studies in the UK have shown that 50 compressions in a row can be performed well by ordinary lay rescuers[9, 10]. A quantitative analysis is as follows. Suppose that a person doing chest compressions uses ideal straight-arm technique, such that torso weight is used for chest compression and the work involved in the vertical dimension is done in lifting the torso between compressions. Suppose one lifts the torso 2 inches between chest compressions and lifts the same torso 20 inches after bending down to deliver a pair of ventilations. Then the work per chest compression (given by force multiplied by distance) is torso weight times 2 inches, which we can call "2 torso-inches" for short. The work per ventilation is torso weight times 20 inches, which we can call 20 "torso-inches" for short. Table 3 compares the power or work rate required in torso inches/sec for 15:2 and 50:2 CPR, assuming that the two ventilations take 5 seconds and the compression rate is 90/min. The work of 50:2 is virtually identical to that for 15:2 in the vertical or "lifting" dimension, excluding the work of shifting laterally from chest to head and back, which is clearly greater for 15:2.

Historically, the problem of sub-optimal compression to ventilation ratios was compounded when compression rate was increased from 60/min to 90/min, and most recently in the year 2000, to 100/min. Consider first the case in which the optimum is defined in terms of maximal oxygen delivery only ($\alpha = 1$). In this case from expression (6)

$$x^* = \sqrt{\frac{a}{b}} = \sqrt{\frac{\frac{T}{t}}{\frac{Q_{MAX}\,s\,t}{(v_T - v_D)}}} = \frac{1}{t}\sqrt{\frac{(v_T - v_D)\,T}{Q_{MAX}\,s}} \quad . \tag{7}$$

Note that x^* is proportional to 1/t, which is the compression rate. Likewise, since a = T/t, x^* is proportional to 1/t for any value of α in expression (6). This means that if one increases the rate of chest compression by a certain percentage, it is prudent to increase the recommended compression to ventilation ratio by the same percentage also.

Suppose that 15:2 had been the optimum compression to ventilation ratio with 60/min compressions under the original CPR guidelines. Then when the recommended compression rate was increased to 90/min, the compression to ventilation ratio should have been automatically increased to 23:2, simply by virtue of the fact that the compression rate had increased. When the recommended compression rate was further increased to 100/min, the compression to ventilation ratio should have been automatically increased to 25:2. Actually 15:2 never was optimal for standard CPR, but failure to adjust ventilation as the compression rate is increased has further compounded the problem.

4. Conclusion

It is only now in the era of serious consideration of CPR simplification[16, 19] and reluctance to perform mouth-to-mouth ventilation[2] that we have begun to reconsider how much ventilation is really needed. The currently recommended 15:2 compression to ventilation ratio is based upon an overly optimistic estimate of the amount of pulmonary capillary perfusion that can be generated during standard CPR. At least half of these ventilations are unnecessary. Valuable time for perfusion is wasted throughout the attendant interruptions of chest compression, during which blood flow falls to zero. These periods of near zero flow must be averaged with periods of marginal flow during chest compression to reckon the overall effectiveness of CPR, which, not surprisingly, is sub-marginal in many cases. By simply converting from a 15:2 to a 50:2 compression to ventilation ratio, a modest but meaningful 7 to 33 percent improvement in oxygen delivery is achieved (Figure 2) and perhaps an 18 to 80 percent increase in overall benefit (Figure 3). Such an improvements are well worth having, especially since unnecessary ventilations also predispose to gastric inflation with subsequent vomiting and aspiration.

5. A Call for Action

One would hope that adjustment of compression to ventilation ratio for basic life support could be accomplished rather quickly worldwide. Innovation by adding something new requires proof of safety and efficacy of the new method. There is a long hard road to consensus guidelines, upon which many decision makers must agree. However innovation by subtracting something—in this case needless ventilations—may be an easier task. By simply eliminating interruptions of chest compression we can increase the quality of standard CPR without penalty and essentially without cost. Why wait?

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Appendix 1. Mean forward flow as a function of the compression to ventilation ratio.

Suppose that forward flow falls to zero during ventilatory pauses and that the rise time for resumption of full flow is roughly equal to the fall time, which is reasonable for standard CPR. Then, using the definitions in Table 1, true mean flow,

$$\overline{Q} = Q_{MAX} \cdot \frac{n_1 t}{n_2 T + n_1 t} = Q_{MAX} \cdot \frac{x}{T/t + x} \ , \qquad \text{(A1.1)}$$

where $x = \frac{n_1}{n_2}$ is the compression/ventilation ratio.

Appendix 2. Change of the oxygen content of blood in the lungs and in the periphery during CPR as a function of the compression to ventilation ratio.

For simplicity, assume the oxygen-blood dissociation curve is linear from zero to 20 ml O_2/100 ml blood at 100 mmHg. This point is equivalent to 0.2 ml O_2/ml blood at f_A = 100 mmHg / 760 mmHg (atmospheric pressure) = 0.133 ml O_2/ml gas. Then the slope, s , of the oxygen-blood dissociation curve is
s = (0.2 ml O_2/ml blood) / (0.133 ml O_2/ml gas) = 1.5 ml gas/ml blood.

In the low flow circumstances of CPR the oxygen taken up by blood in equilibrium with any particular alveolar oxygen concentration, f_A , is well approximated by the simple expression $\Delta c \cong s \cdot f_A$, with offsetting errors. Here we underestimate the oxygen content of arterial blood because of the linear approximation to the oxygen-blood dissociation curve above. However, we also underestimate the oxygen content of mixed venous blood in low flow state of CPR, by assuming it is zero. This simple approximation captures the essence of the fact that oxygen delivery depends critically on alveolar oxygen concentration. One cannot fail to ventilate indefinitely and maintain all of the benefits of forward flow of blood.

Now to solve for $\Delta c \cong s \cdot f_A$, in terms of compression/ventilation ratio, x, we need an expression for f_A in terms of other relevant variables in Table 1, including x. This expression can be obtained from the following steady-state balance: tracheal oxygen inflow = tracheal oxygen outflow + oxygen delivery to the body. In symbols

$$(v_T - v_D)Rf_I = (v_T - v_D)Rf_A + \overline{Q} \cdot s \cdot f_A \ , \qquad \text{(A2.1)}$$

where R is the average rate of ventilation over a full compression/ventilation cycle.

Solving A2.1 for f_A , we have

$$f_A = \frac{(v_T - v_D) R f_I}{(v_T - v_D) R + s\overline{Q}} = \frac{(v_T - v_D) f_I}{(v_T - v_D) + s\dfrac{\overline{Q}}{R}} \quad . \tag{A2.2}$$

Next we can introduce the variable, x, by noting that both mean blood flow and mean respiratory rate, R, are functions of x . From Appendix 1

$$\overline{Q} = Q_{MAX} \cdot \frac{n_1 t}{n_2 T + n_1 t} = Q_{MAX} \cdot \frac{x}{T/t + x} \quad . \tag{A2.3}$$

Similarly,

$$R = \frac{n_2}{n_2 T + n_1 t} = \frac{1}{T + xt} = \frac{1}{t} \cdot \frac{1}{T/t + x} \quad . \tag{A2.4}$$

Dividing (A2.3) by (A2.4) we have $\dfrac{\overline{Q}}{R} = Q_{MAX}\, t\, x$, which can be substituted into (A2.2) to obtain

$$f_A = \frac{(v_T - v_D) f_I}{(v_T - v_D) + Q_{MAX}\, s\, t\, x} \quad . \tag{A2.5}$$

In turn,

$$\Delta c_{O_2} \cong s f_A = \frac{s\,(v_T - v_D) f_I}{(v_T - v_D) + Q_{MAX}\, s\, t\, x} \quad . \tag{A2.6}$$

Appendix 3. Solving for the optimum compression to ventilation ratio.

Suppose

$$F(x) = \left(\frac{x}{a + x}\right)^{\alpha} \frac{1}{1 + bx} \ , \tag{A3.1}$$

and we wish to find x^* corresponding to the maximum value of f(x).

Differentiating with respect to x and setting the derivative equal to zero,

$$F'(x) = 0 = \left(\frac{x}{a + x}\right)^{\alpha} \frac{-b}{(1 + bx)^2} + \frac{\alpha}{1 + bx}\left(\frac{x}{a + x}\right)^{\alpha - 1}\left[\frac{1}{a + x} - \frac{x}{(a + x)^2}\right], \tag{A3.2}$$

which after rearrangement and simplification becomes the quadratic equation

$$x^2 - a(\alpha - 1)x - \frac{a}{b}\alpha = 0 \ . \qquad \text{(A3.3)}$$

Solving for x using the quadratic formula gives

$$x^* = \frac{a(\alpha - 1) \pm \sqrt{a^2(\alpha - 1)^2 + 4\frac{a}{b}\alpha}}{2} \ . \qquad \text{(A3.4)}$$

Note that if $\alpha = 1$, then $x^* = \sqrt{\frac{a}{b}}$; hence the positive root is the meaningful one.

So,

$$x^* = \frac{1}{2}\left(a(\alpha - 1) + \sqrt{a^2(\alpha - 1)^2 + 4\alpha\frac{a}{b}} \right), \qquad \text{(A3.5)}$$

which can be easily verified by plotting F(x).

Table 1. Nomenclature and standard values for computations.

Variable	Definition	Standard CPR Value and Units
f_A	Fraction of oxygen in alveolar gas	0.14[25]
f_I	Fraction of oxygen in inspired gas exhaled by rescuer during one-rescuer CPR	0.16[26]
n_1	Number of compressions per complete compression/ventilation cycle	15
n_2	Number of ventilations per complete compression/ventilation cycle	2
Q_{MAX}	Maximum forward blood flow during continuous chest compressions	1.00 L/min = 1000 ml/min
$\overline{Q}$	Mean forward blood flow including ventilatory pauses	0.67 L/min = 670 ml/min
t	Chest compression/relaxation time	1/100 min = 0.01 min
T	Average time for one ventilation (ideal value) Average time for one ventilation (practical value)	2.5 sec = 0.042 min 8.0 sec = 0.133 min
R	Average rate of ventilations in CPR	8/min
s	Average slope of oxygen-blood dissociation curve in physiologic range	1.50 ml alveolar gas/ml blood
v_T	Tidal volume	Normal: 500 ml air[25] CPR: 700 ml[1]
v_D	Anatomic dead space of tracheobronchial tree	150 ml air[25]
D_{O_2}	Oxygen delivery	250 ml oxygen/min[25]
x	Compression ventilation ratio (n_1 / n_2)	7.5 (Guideline value)

Table 2. Statistical parameters for Monte Carlo simulations.

Parameter	**Mean ± 1 SD**	**Units**
Maximum flow, Q_{MAX}	900 ± 200*	ml blood / min
Ideal single breath time, T	0.042 ± 0.01	min
Lay single breath time, T	0.133 ± 0.01	min
Compression rate, 1/t	100 ± 10	1 / min
Tidal volume, V_T	800 ± 200**	ml gas
Inspired O_2, F_I	0.16 ± 0.02	ml O2 / ml gas
Dead space, v_D	150	ml gas
Blood O_2 affinity, s	1.5	ml gas / ml blood

* Here it is assumed that real world rescuers do somewhat less effective CPR than laboratory investigators, and there is wide variation in effectiveness.

** Current guidelines[1] recommend 70 ml/kg or 700 to 1000 ml tidal volume.

Table 3: Comparative work rates in "torso-inches" per second

	15:2 CPR	50:2 CPR
Compression work (torso inches)	15x2=30	50x2=100
Ventilation work (torso inches)	20	20
Cycle time (sec)	15	38
Work rate (torso inches/sec)	50/15=3.3	120/38=3.2

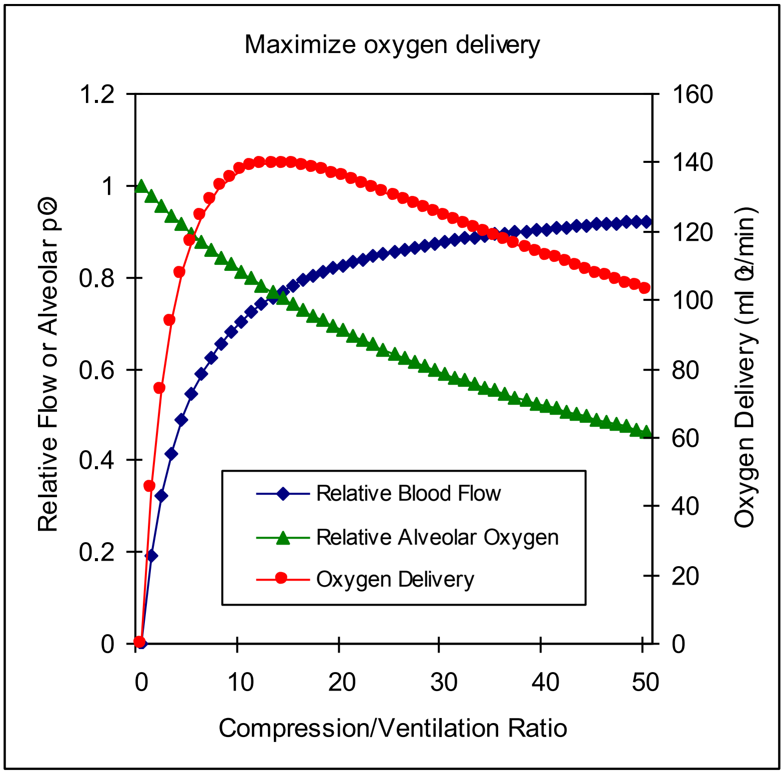

Figure 1(a)

Fig. 1. Components of oxygen delivery as a function of compression to ventilation ratio in a physiological model of cardiac arrest and CPR.

(a) Results for professionally trained rescuers, assumed to deliver two rescue breaths in 5 seconds.

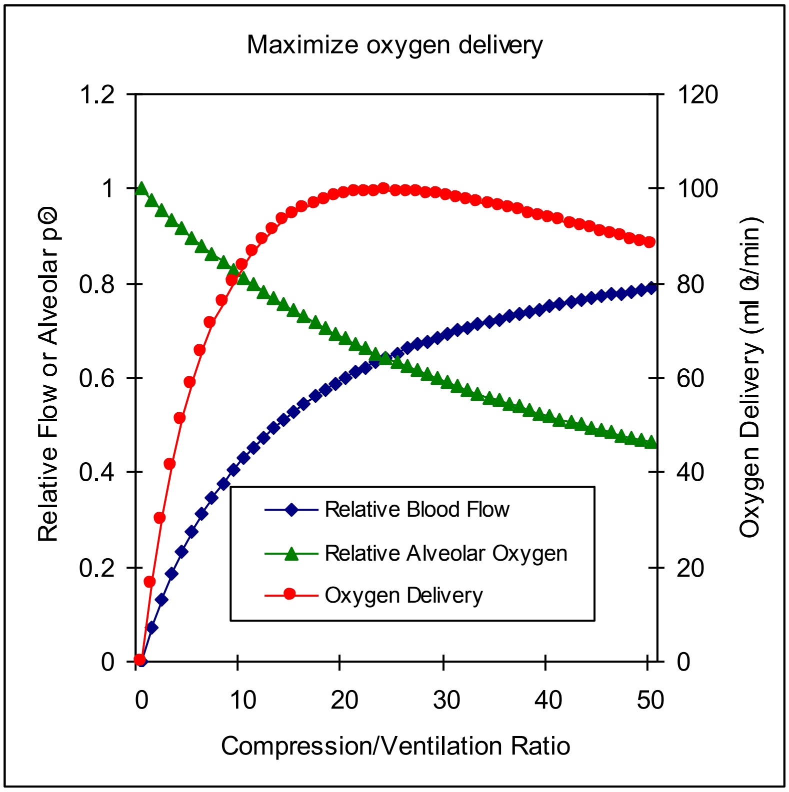

Figure 1(b)

(b) Results for lay rescuers, assumed to deliver two rescue breaths in 16 seconds.

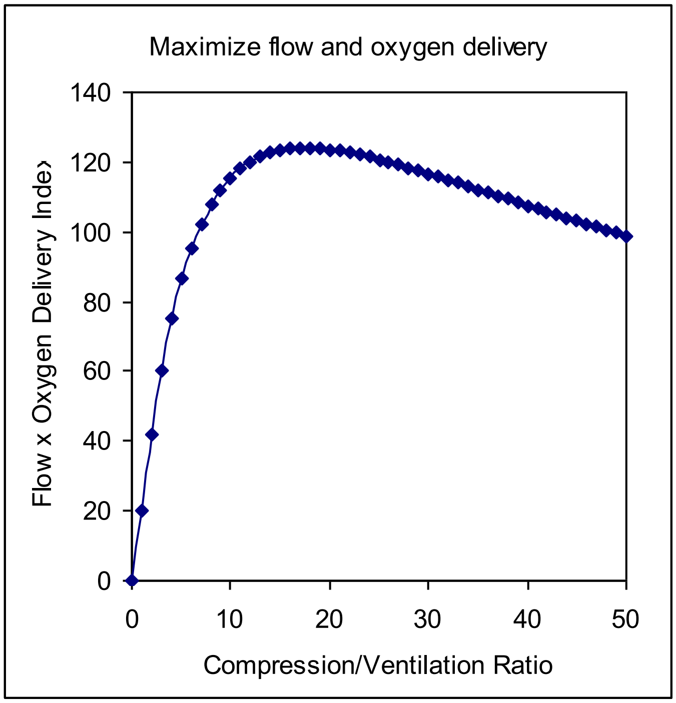

Figure 2(a)

Fig. 2. Index of combined blood flow and oxygen delivery as a function of compression to ventilation ratio in a physiological model of cardiac arrest and CPR.

(a) Results for professionally trained rescuers, assumed to deliver two rescue breaths in 5 seconds.

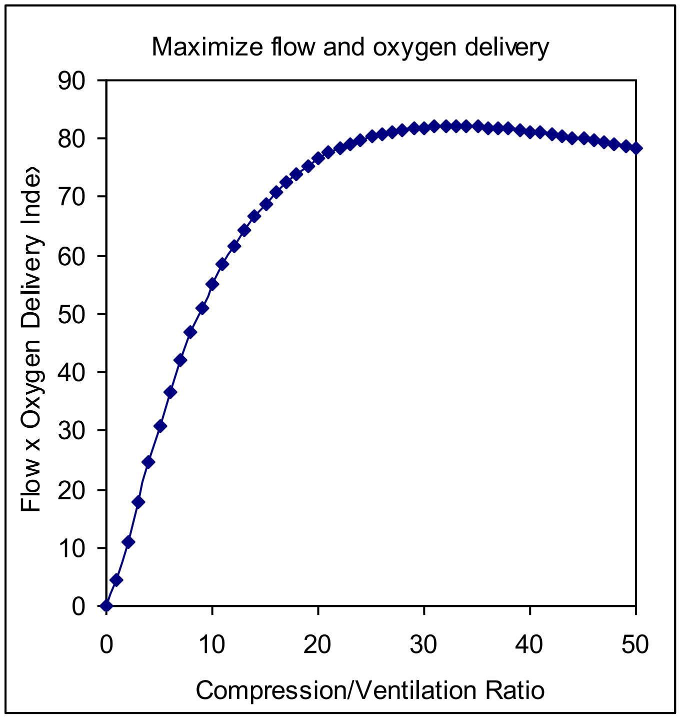

Figure 2(b)

(b) Results for lay rescuers, assumed to deliver two rescue breaths in 16 seconds.

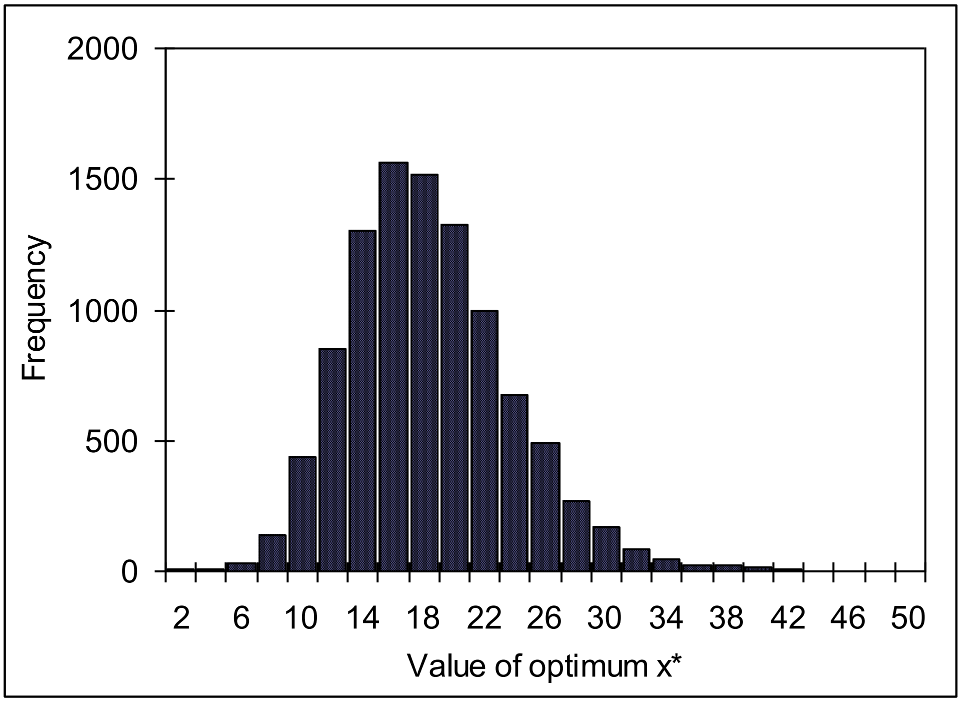

Figure 3(a)

Fig. 3. Histograms of optimal values of the compression to ventilation ratio, x, for 10,000 simulated resuscitations, in which parameters of rescuer performance were varied at random. Details of the stochastic model are presented in Table 2. (a) Results for professionally trained rescuers, assumed to deliver each of two rescue breaths in 0.042 ± 0.01 min (2.5 ± 0.6 sec).

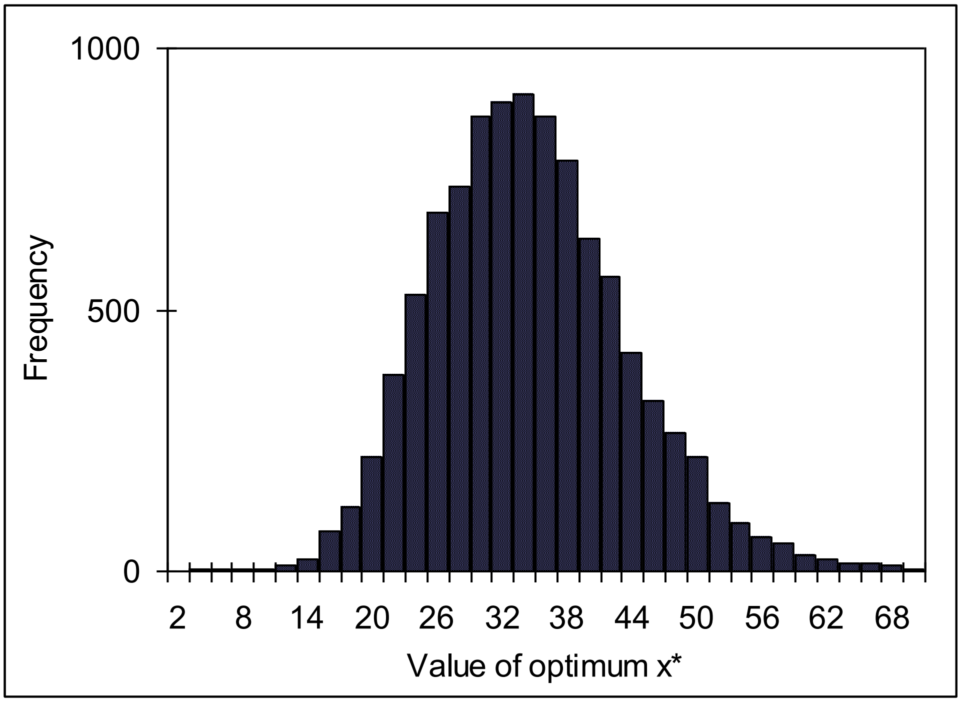

Figure 3(b)

(c) Results for lay rescuers, assumed to deliver each of two rescue breaths in 0.133 ± 0.01 min (8.0 ± 0.6 sec).