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Optimizing Chest Compression to Rescue Ventilation Ratios During One-Rescuer CPR by Professionals and Lay Persons: Children are Not Just Little Adults

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Optimizing Chest Compression to Rescue Ventilation Ratios During One-Rescuer CPR by Professionals and Lay Persons: Children are Not Just Little Adults

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Abstract

Objective: To estimate the optimum ratio of chest compressions to ventilations for one-rescuer CPR that maximizes systemic oxygen delivery in children.
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 adapted from the former work of Babbs and Kern. These equations were solved explicitly as a function of body weight, using scaling algorithms based upon principles of developmental anatomy and physiology.
Results*:* The optimal compression to ventilation (C/V) ratios for infants and younger children increase sharply as a function of body weight. Optimal C/V ratios are lower for professional rescuers, who take less time to deliver a rescue breath, than for lay rescuers, who interrupt chest compressions longer to perform ventilations. For professional rescuers the optimal C/V ratio, x*, is approximately $1.6\sqrt{W}$ where the W is the patient's body weight in kg. For lay rescuers the optimum C/V ratio is approximately $2.8\sqrt{W}$. These values can be approximated for children and teens by the following rules of thumb, based upon the age of the victim: "5 + one half the age in years" for professional rescuers and "5 + age in years" for lay rescuers.
Conclusions: Compression to ventilation ratios in CPR should be smaller for children than for adults and gradually increase as a function of body weight. Optimal CPR in children requires relatively more ventilation than optimal CPR in adults. A universal compression/ventilation ratio of 50:2, targeted to optimize adult resuscitation, would not be appropriate for infants and young children.

Key words: Cardiopulmonary resuscitation (CPR); Children, Coronary perfusion pressure; Guidelines; Heart arrest; Tidal volume

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1. Introduction

Pediatric cardiac arrest is uncommon and has a broad range of etiologies. These etiologies differ from the preponderance of ischemic heart disease and ventricular fibrillation causing cardiac arrest in adults. In general, pediatric out-of-hospital arrest is characterized by a progression from hypoxia and hypercarbia to respiratory arrest, which is followed by bradycardia and asystolic cardiac arrest[1-3]. Current pre-hospital treatment strategies are often adapted from adult treatments, because so few adequate clinical studies have been conducted in children[4]. Basic life support interventions currently recommended for pediatric cardiac arrest are essentially similar to those recommended for adults, with a somewhat greater emphasis on early ventilation[4].

Although previous studies demonstrate that compression/ventilation ratios influence the effectiveness of CPR[5, 6], the optimal compression to ventilation ratio for professional rescuers or for lay persons performing one-rescuer CPR in children is not known[7]. Finding the best ratio is complicated by the necessity for a single rescuer to discontinue chest compressions to administer ventilations. Recent videotape analysis of lay rescuers performing 15:2 adult CPR on manikins shows that the pause in chest compression required to deliver two ventilations averages about 16 seconds[8, 9]. This delay is much longer than the ideal guideline value of 5 seconds for two ventilations in adults[10]. Hence in a practical, real world setting, with a compression rate of 100/min, chest compressions would be interrupted for ventilations a majority of the time (9 seconds for 15 compressions, 16 seconds for 2 ventilations). Studies of CPR by trained physicians and nurses on infant and child manikins suggest that interruptions in 1-rescuer CPR greatly impact the quantity and quality of compressions delivered[7, 11]. In particular, 30 percent of cycle time was required for transfers between head and chest needed to deliver rescue breaths, and 24 percent of cycle time was used for giving rescue breaths themselves. Chest compressions were delivered for only 46 percent of cycle time[7]. Since one lone rescuer can either compress the chest or ventilate, but cannot do both, there must be an optimum compromise between the two activities, i.e. an optimum C/V ratio, which maximizes oxygen delivery to the myocardium, brain and systemic circulation.

Emerging data for adult basic life support suggest that up to as many as 50 or 100 compressions followed by 2 ventilations may be optimal for adults[6, 8, 9, 12] who are resuscitated by a single rescuer. Given that the quality of chest compressions needs to be maintained[13], the developmental anatomy and physiology of children may well imply different optimal ventilation strategies for premature neonates, neonates, infants, children, and adolescents, and adults. Pilot data on pediatric mannequins[5] suggest that 3:1 and 5:1 C/V ratios favor ventilation; whereas a 15:2 C/V ratio favors circulation. A large number of such studies could be done on manikins and pediatric patients of many different sizes. Inevitably, there would be some discrepancies in the methods and results, provoking controversy and calls for further research. A totally empirical, evidence-based process for discovering optimal C/V ratios in children could take decades. In the meantime, a compact, but comprehensive theory of how optimal C/V ratios change as a function of body weight could greatly assist guideline developers to develop reasonable recommendations for pediatric resuscitation.

In the present paper we extend the mathematical and physiological approach of Babbs and Kern[6] to find the optimum compression/ventilation ratio for children of varying body size. For simplicity, optimum is defined here in terms of total systemic oxygen delivery. For any particular distribution of cardiac output to various organs, governed in part by the ratio of alpha to beta-adrenergic tone, total oxygen delivery correlates with regional oxygen delivery to vital organs such as the heart and brain. Parameters are calculated using either "ideal CPR", as taught in CPR courses and approximated by professional rescuers, or "real world CPR ", as done by lay-rescuers, who take much more time to administer rescue breaths. The results suggest that the optimal compression to ventilation ratios for infants and children are much less than those for adults and vary strongly as a function of body weight.

2. Methods

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 x* at which the desired result is maximized. Suppose, for example, that the desired result is maximal systemic oxygen delivery, as is most often considered in this context[6, 14, 15]. Using the physiologic and mathematical approach of Babbs and Kern[6]—in particular their equation (7)—the optimal compression to ventilation ratio in CPR is given by

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

In this expression CR is the chest compression rate in compressions per minute, v_T is the tidal volume in ml, v_D is the anatomic dead space of the patient's airways in ml, T is the average time required to deliver one ventilation in minutes, Q_{MAX} is the maximal forward flow in ml/min that can be obtained if chest compressions are not interrupted for ventilation, and s is the slope of the oxygen-hemoglobin dissociation curve in units of ml of gas/ml of blood. Expression (1) states that the number of compressions per ventilation needed to optimize oxygen delivery depends on six parameters.

Consider first the ventilation time, T. During time T compressions are interrupted in single rescuer CPR, because the rescuer must go to the head to perform a mouth-to-mouth rescue breath. During this time there are no chest compressions, and forward flow falls to zero. Relatively long pauses in chest compression required for ventilation cause disturbingly long interruptions blood flow. In turn, the average systemic perfusion pressure over a complete compression/ventilation cycle is reduced. Thus when T is long, as happens when unpracticed lay rescuers perform CPR[8, 9], better oxygen delivery can be obtained by increasing the number of compressions between ventilations. Then flow interruptions become relatively less important, and ventilation and perfusion become better matched.

Another factor is tidal volume minus anatomic dead space—that is, the amount of fresh air getting to the lungs, here denoted $v_T - v_D$. When effective ventilation is increased, more compressions can be added per ventilation to use up the extra oxygen provided by the increased tidal volume. The increased blood flow from more compressions restores the original match between ventilation and perfusion. On the perfusion side of the balance, the Q_{MAX} term in the denominator of equation (1) can be similarly understood in terms of ventilation perfusion matching. For example, if Q_{MAX} increases, then each compression must produce more flow. In turn, fewer compressions are needed to match a given number of ventilations.

Still another factor is the compression rate, CR. Consider a one-rescuer paradigm, in which the rule is give "give n compressions, then give m rescue breaths", where for example n = 5 and m = 1 in child CPR or n = 15 and m = 2 in adult CPR. If the compression rate is increased from, say, 60/min to 100/min, then the time to deliver a fixed number, n, of compressions is reduced. In turn a fixed ventilatory pause time, T, during which there are no compressions, becomes a relatively greater proportion of total compression-ventilation cycle time. In this case adding a greater number of compressions at the higher rate between ventilations tends to restore the balance between ventilation time and perfusion time, which is an important determinant of oxygen delivery.

Thus one can appreciate that the formulation of equation (1) makes sense in terms of the physiology of ventilation and perfusion as well as in terms of the mathematics, which is derived in detail in reference[6]. In the present paper we are concerned with possible differences in equation (1) between children and adults, as well as among children of different ages and body weights. To get a feel for this problem, it is useful to consider whether one would logically expect such differences to be present on the basis of known effects of scale in anatomy and physiology[16, 17].

2.2 Approach to scaling x as a function of body weight*

Scaling rules in biology describe the structural and functional consequences of changes in body size among otherwise similar organisms[17]. To deal with the question of whether the optimum compression to ventilation ratio, x*, is different for children versus adults, let us adopt a simplified scaling paradigm along the lines of Schuder et al.[18] for scaling of defibrillation shock strength. Certain relationships between the linear dimensions of an animal, L, its weight, W, and its metabolic rate are generally valid for any set of warm-blooded animals of similar body shape. For purposes of simplicity, we assumed a person maintains essentially the same shape, as he or she grows older. The classical developmental differences in the relative proportions of human head size, torso size, and leg length were assumed of limited importance from a metabolic standpoint during CPR. In this case lean body mass to first approximation scales with the cube of any particular linear dimension. Body surface area scales with the square of the linear dimension. For homeotherms of the same species, basal metabolic rate, and in turn oxygen consumption, scale approximately with body surface area—the predominate site of heat loss. The related notion that cardiac output scales with body surface area, more accurately than with body weight, has lead to the concept of cardiac index, or forward blood flow per square meter of body surface area[19].

In the following discussion we use the symbol $\propto$ to indicate proportionality—that is the quantity to the right of the $\propto$ sign is equal to the quantity on the left, multiplied by a constant. Note for the $\propto$ operator that (1) if A $\propto$ B then B $\propto$ A; (2) if A $\propto$ B and also B $\propto$ C, then A $\propto$ C; and (3) if A $\propto$ B and also A $\propto$ C, then A $\propto$ B+C. Definitions of the relevant anatomic and physiologic variables are provided in Table 1.

Table 1. Nomenclature for scaling algebra

Symbol	**Definition**	**Units**
BSA	Body surface area	m^2
k	Any constant	various
RR	Respiratory rate	min^{-1}
T	Average time required to perform one rescue breath, during which chest compressions are interrupted	min
t_{in}	Inspiratory time	min
t_{out}	Expiratory time	min
v_T	Tidal volume	ml air
W	Body mass	kg

Using this notation, we can write

$$W \propto L^3 \ , \qquad (2)$$

that is, weight is proportional to the cube of any linear dimension, and

$$\text{Oxygen consumption} \propto L^2 \propto W^{2/3} \ . \qquad (3)$$

One can explore the effects of scale on the optimal compression to ventilation ratio, x*, by first exploring the effects of scale upon the various components of expression (1), namely tidal volume minus dead space, ventilatory pause time, and maximal cardiac output during CPR. As shown below, it is possible to find a reasonable expression for each of these variables as a function of body weight, W. When these are inserted into equation (1), the result is an expression for x* as a function of W that can be used both for adults and for children of all sizes.

2.3. $v_T - v_D$ as a function of W

Tidal volume per kilogram of lean body weight is relatively constant for children of all ages, and indeed for mammals in general[17, 20], and amounts to about 7 ml/kg (Table 2). Similarly, dead space volume is about 2 ml per kg body weight. Hence, the scaling rule for these parameters as a function of weight is straightforward. It is $v_T - v_D = k_1 W$, where k_1 is about 5 ml/kg. If one consistently adopts moderate over-ventilation (10 ml/kg tidal volume), as is recommended in the CPR guidelines, then k_1 is about 8 ml/kg. Thus tidal volume minus dead space is proportional to body weight, or $v_T - v_D \propto W$.

Table 2. Respiratory rates and tidal volumes for children of different ages*

Age	**Weight (kg)**	**Resp. Rate (min-1)**	**Tidal Volume (ml)**	**Tidal volume (ml/kg)**
Infant	4	35	22	5.5
6 mos	7.5	30	57	7.6
2 years	10	25	70	7.0
6 years	20	21	140	7.0
10 years	32	18	220	6.9
18 years	70	13	480	6.8

* Data from Radford, NEJM, 1955, and standard growth charts, and Seidel and Henderson, Pre-hospital Care of Pediatric Emergencies, 1987. Tidal volume per kg is relatively constant throughout the growth and development of children.

2.4. T as a function of W

We can gain some insight into scaling of the amount of time, T, it takes to blow in one rescue breath during CPR from scaling rules for the amount of time, t_{in}, it takes for a person to inspire one normal breath at rest. If tidal volume and respiratory rate remain normal for different sized persons at rest, then resting oxygen consumption is proportional to the minute volume of ventilation, namely,

Oxygen consumption $\propto (v_T - v_D) \cdot RR = \dfrac{v_T - v_D}{t_{in} + t_{out}}$. Since tidal volume minus dead space is proportional to body weight, W, then we can write

$$\text{Oxygen consumption} \propto \frac{W}{t_{in} + t_{out}} \propto \frac{W}{t_{in}}. \tag{4}$$

The last step in (4) is reasonable because the ratio of inspiratory to expiratory time is roughly constant (1:1.2)[21]. Combining equations (3) and (4), we have

Oxygen consumption $\propto W^{2/3} \propto \frac{W}{t_{in}}$, or

$$t_{in} \propto W^{1/3}. \qquad (5)$$

Thus normal inspiratory time is proportional to the cube root of body weight. Besides the time required to blow in one tidal volume, t_{in}, there is another component to ventilation time, T, in single-rescuer CPR. This is the round trip time for the rescuer to leave the chest and move, to the head to deliver a mouth-to-mouth rescue breath, and then to return to the chest to resume chest compressions. In smaller individuals such as children the time for movement is less because the physical distance is less. It is quite reasonable to suppose that the shift time is roughly proportional to the distance between the head and the chest, which is proportional to L, which in turn is proportional to $W^{1/3}$. Since both inspiratory time and rescuer shift time are each proportional to $W^{1/3}$, we can write the scaling rule for total CPR ventilation time per breath as

$$T = k_2 W^{1/3}. \qquad (6)$$

2.5. CO_{MAX} as a function of W

In children the ratio of maximal cardiac output during CPR to normal cardiac output when the heart is beating is probably greater than in adults. Such a difference is likely to be true owing to greater chest resiliency in children, a greater degree of cardiac compression vs. thoracic pumping[22], and a greater ratio of compression depth to chest diameter. Note that the recommended compression depth in children is relatively greater than in adults. For adults the recommended depth is 1.5 to 2 inches, which is approximately 20 percent of the anteroposterior diameter of the adult chest. In smaller children the recommended depth is 1 to 1.5 inches, or 33 to 50 percent of the anteroposterior diameter[10]. Recall that the depth of chest compression in CPR is one of the major factors that determine forward flow[23]. Hence, to the extent that the foregoing effects occur, CPR will generate greater forward flow, Q_{MAX}, in children than in adults.

Although these effects are not as yet well studied, for simplicity, let us assume that

$$\frac{CO_{MAX}}{CO_{Normal}} \propto \frac{1}{L} \propto \frac{1}{W^{1/3}}. \qquad (7)$$

For example, if this ratio were roughly 15% for a 150 cm long person, it would scale to 75% for a 30 cm long person. Recall that normal cardiac output is proportional to body surface area or $W^{2/3}$. Then, we can write

$$CO_{MAX} \propto \frac{1}{W^{1/3}} \cdot CO_{Normal} \propto \frac{W^{2/3}}{W^{1/3}} = W^{1/3}. \tag{8a}$$

That is, it is reasonable to expect that

$$CO_{MAX} = k_3 W^{1/3}. \tag{8b}$$

2.6. x as a function of body weight*

Now at last, we can combine the scaled parameters of equation (1) as follows, to obtain the optimal C/V ratio, x*, as a function of body weight, W.

$$x^* = CR \cdot \sqrt{\frac{(v_T - v_D)T}{Q_{MAX} s}} = CR \cdot \sqrt{\frac{k_1 W \cdot k_2 W^{1/3}}{k_3 W^{1/3} s}} = CR \cdot k \cdot \sqrt{W} \ , \tag{9}$$

where $k = \sqrt{\frac{k_1 \cdot k_2}{k_3 s}}$.

Further, according to international guidelines, the compression rate, CR, is now standardized at 100/min for both adults and children (for infants the recommended rate is "at least 100/min"[10]). That is, compression rate CR is also a constant, $k_0 = 100/\text{min}$. Combining all the constants, k_0, k_1, k_2, k_3, and s, we come down to a rather simple scaling rule:

$$x^* \propto \sqrt{W} \quad \text{or} \quad x^* \propto W^{0.5}. \tag{10}$$

2.7. Sensitivity analysis

There are plausible alternatives to expression (10). Different assumptions regarding the scaling rule for basal metabolic rate, and in turn oxygen consumption and cardiac output, lead to slightly different scaling rules for the optimal C/V ratio. For example if BMR is proportional to the 0.75 power of body weight, as suggested in reference 17, then $x^* \propto W^{0.4125}$. If BMR is proportional to the 0.54 power of body weight, as suggested in reference 24, then $x^* \propto W^{0.625}$. Here the compromise exponent of 0.5 is simple, intermediate, and understandable in terms of steady-state heat loss from the body surface area. Another alternative scaling rule could be proposed by those who argue that CPR pumping efficiency, CO_{MAX} / CO_{Normal}, is a constant for children versus adults, rather than scaling inversely with body length, as suggested in expression (8).

To explore the effects of these alternative assumptions, we performed a sensitivity analysis. Six alternative models spanning the spectrum of plausible assumptions are defined in Table 4. Here the variable, a, is the scaling exponent of body weight for tidal volume, so that $TV \propto W^{a}$. The variable, b, is the scaling exponent for basal metabolic rate, oxygen consumption, and cardiac output, so that $Q_{MAX} \propto W^{b}$. The variable, -e, is the scaling exponent for CPR efficiency, so that $CO_{MAX} / CO_{normal} \propto W^{-e}$. It is easily shown along the lines of expressions (3) and (10) that the generalized scaling exponent for x* is given by the expression $a - b + e/2$, which was evaluated for the 6 models in Table 4. The results allow one to assess the sensitivity of the major conclusions of our paper to such modifications in the initial assumptions.

Table 3. Average adult parameters used for theoretical calculations

Parameter	**Value**	**Units**
Compression rate, CR	100	1 / min
Maximum flow, Q_{MAX}	900	ml blood / min
Single breath time, T, for professional rescuers	0.042	min
Single breath time, T, for lay rescuers	0.133	min
Tidal volume, v_T	700	ml gas
Dead space, v_D	150	ml gas
Blood O_2 affinity, s	1.5	ml gas / ml blood

Table 4. Alternative scaling rules for sensitivity analysis

Model	**a**	**b**	**e**	**Exponent in** $x^* \propto W^{a-b+e/2}$
1	1	2/3	1/3	0.500
2	1	2/3	0	0.333
3	1	3/4	1/3	0.417
4	1	3/4	0	0.250
5	1	1/2	1/3	0.667
6	1	1/2	0	0.500

3. Results

3.1. Suggested square root scaling rule

Specific numerical results of the forgoing analysis indicate that the optimal compression to ventilation ratio, x*, becomes systematically less as the size of the victim is reduced from a 70 kg adult to a 5 kg infant. If we evaluate expression (1) for the mean values in Table 3 for a 70 kg adult we obtain $x^*(70) = 13.1$, that is 13 compressions for each ventilation, assuming a ventilation time of 5-sec/2 breaths that is characteristic of well-trained adult rescuers. The corresponding value for once trained lay rescuers, who take 16 sec to deliver 2 breaths,[8, 9] is $x^*(70) = 23.3$ compressions for each ventilation. Then, using the proportionality of expression (10), we evaluated the optimal ventilation compression ratio for individuals of different lean body weights as

$$x^*(W) = x^*(70)\sqrt{\frac{W}{70}} . \qquad (11)$$

This formula gives $x^* = 1.6\sqrt{W}$ for ventilation times that are characteristic of professional rescuers and $x^* = 2.8\sqrt{W}$ for ventilation times that are characteristic of lay rescuers.

These two square-root functions are plotted using open symbols in Figure 1. The curves predict in a quantitative manner that optimal compression/ventilation ratios for children may be very much less than those for adults. For those who have difficulty estimating a child's weight in kilograms and computing square roots, a practical rule of thumb can be used, based upon the child's age from zero to 20 years. The solid data points in Figure 1 utilize the rules "x* = 5 + (age in years)/2" for professional rescuers and "x* = 5 + age in years" for lay rescuers. These points were calculated using average values for weights of children at various ages[25]. They approximate the theoretical scaling curves reasonably well.

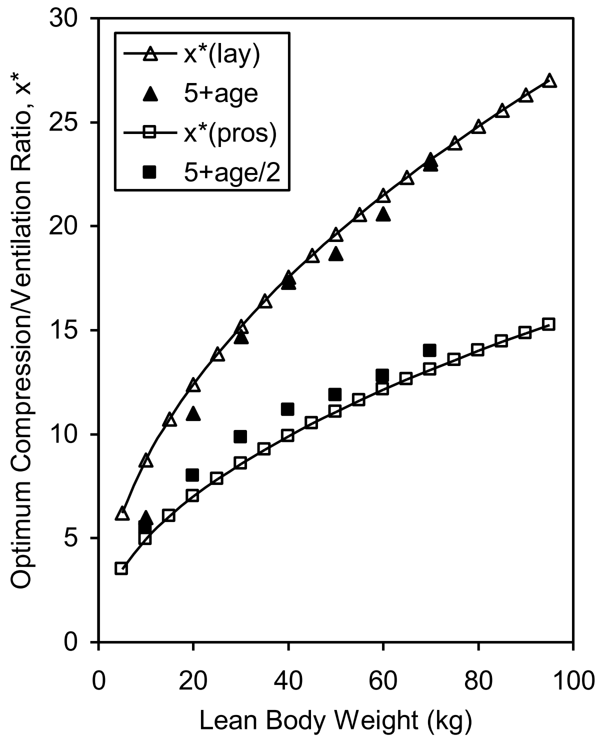

Figure 1. Scaling rules for optimum C/V ratios in pediatric basic life support. Open symbols represent theoretical compression/ventilation ratios for optimal oxygen delivery, scaled for persons having a wide range of body weight. Lay rescuers (lay) are assumed to take 8 sec to deliver one rescue breath in an adult sized individual, in keeping with the observations of Chamberlain and coworkers. Professional rescuers (pros) are assumed to take 2.5 sec to deliver one rescue breath. Solid symbols indicate approximations to the theoretical curves, based upon average body weights of children ages 1 to 18, according to the rules "5 + patient age in years" for lay rescuers and "5 + one half patient age in years" for professional rescuers.

3.2. Sensitivity analysis

Figure 2 shows theoretical optimum C/V ratios as a function of lean body weight for the family of plausible scaling models detailed in Table 4. These models are characterized succinctly by the exponent of lean body weight, W, which ranges from 0.33 to 0.67. On such a graph an exponent of zero would generate a constant value of x*, completely independent of body weight. An exponent of 1.0 (that is x* directly proportional to body weight) would generate a perfectly straight line through the origin.

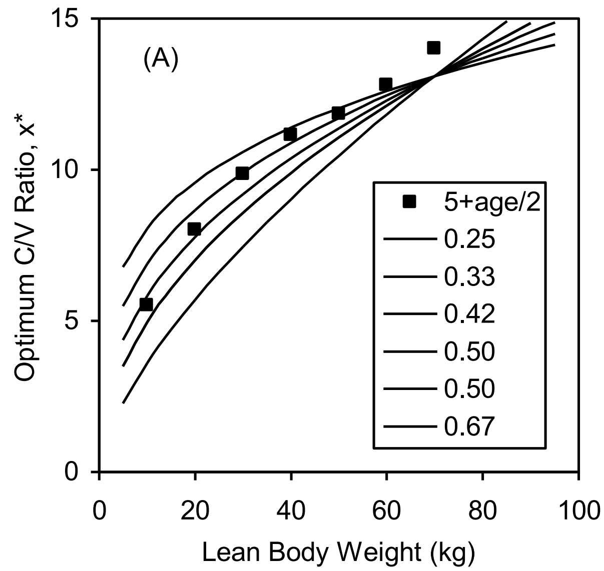

Figure 2(A)

Figure 2. Sensitivity analysis for scaling rules for optimum C/V ratios in pediatric basic life support. The general effect of body size upon the optimum C/V ratio is insensitive to changes in the exponent of body weight. (A) calculations for professional rescuers, (B) calculations for lay rescuers.

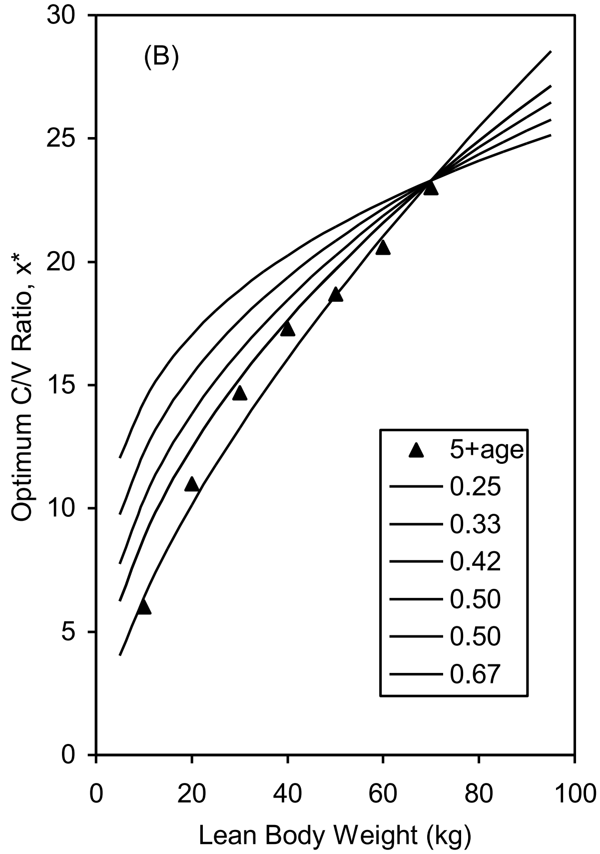

Figure 2(B)

Figure 2. Sensitivity analysis for scaling rules for optimum C/V ratios in pediatric basic life support. The general effect of body size upon the optimum C/V ratio is insensitive to changes in the exponent of body weight. (A) calculations for professional rescuers, (B) calculations for lay rescuers.

Figure 2(A) shows a family of curves for professional rescuers. All curves pass through a common point of 13.1 at 70 kg. In the range of 0 to 70 kg, the top curve represents an exponent of 0.33 and the bottom curve represents an exponent of 0.67. The intermediate curves appear in order of increasing exponent. Only five total curves are shown for the six models, because two of the curves at exponent 0.5 overlap completely. Solid diamonds in Figure 2(A) indicate the "5 plus one half age in years" rule for children and adolescents. This rule approximates results from all six alternative scaling models.

Figure 2(B) shows a similar set of curves for lay rescuers. The common point is at a C/V ratio of 23.3 for a 70 kg adult. Solid triangles indicate the "5 plus age in years" rule for children and adolescents. The general conclusion that optimal C/V ratios for children are smaller than those for adults follows from any of the alternative scaling rules specified in Table 4.

3. Discussion

Tissue oxygen delivery depends upon complex interactions among compression rate, ventilation time, the forward flow generated by CPR, and other factors, most of which depend upon body size. In turn, the optimal technique of CPR may depend upon body size more so than has been appreciated heretofore. One important descriptor of CPR technique is the compression to ventilation ratio. This ratio is especially important for single rescuer basic life support, because a single rescuer must stop chest compressions completely to deliver ventilations.

Babbs and Kern[6] have suggested that a good way to optimize the compression to ventilation ratio for one rescuer CPR is to choose the ratio that maximizes systemic oxygen delivery. Theoretically (ignoring the small amount of ventilation caused by chest compressions themselves) neither compression only nor ventilation only CPR can sustain systemic oxygen delivery. Some intermediate value of the C/V ratio is needed to obtain the best tradeoff between time spent doing chest compressions and time spent doing ventilations. The best intermediate value depends upon factors that can be related in a simple mathematical formula that is based upon classical physiology. The main message of this paper is that these physiologic factors necessarily change as a function of the size of the patient.

Previous studies have shown that C/V ratios influence the effectiveness of CPR in adults[26], and for the sake of simplicity and ease of instruction, some national and international guideline writers have considered a single C/V ratio for all age victims of cardiac arrest. Dorph and coworkers, for example, have proposed that this rate be 15:2 for children as well as adults[27]. (For 15:2 CPR the compression to ventilation ratio is 7.5:1.) According to our calculations, this recommendation is most suitable for a 6-year-old child, weighing 20 kg, who is resuscitated by a professional rescuer. However, in our view, this ratio would be too low for larger adults and too high for smaller children. The “5 plus” rules in Figure 1 for persons aged 0 to 20 may provide a graceful transition from the pediatric world to the adult world, where a C/V ratio of 25:1 or 50:2 is now being advocated for one rescuer CPR[6, 8, 9]. Although arguably appropriate for adults, a universal compression/ventilation ratio of 50:2 applied to all age groups would likely result in underventilation of pediatric patients. This conclusion is especially important because pediatric cardiac arrest is most often the result of prior respiratory arrest with profound hypoxemia, hypercarbia, and respiratory acidosis. Hence many children in cardiac arrest will require extra ventilation above and beyond that needed to optimally deliver oxygen to the periphery.

An important practical issue is whether the differences in theoretically "optimal" C/V rations in children of different sizes are substantial enough to warrant complex, different recommendations for children of different sizes. Here we offer the "5 plus age" and "5 plus one half age" rules as possible compromises. In the future, we speculate that real-time analyses of blood flow, tissue perfusion, tissue oxygenation, chest compression amplitude, ventilation, and ECG waveform are likely to be performed by "smart" automated external defibrillators with voice advisory capability. It will be possible to monitor a rescuer's actual ventilation time, T, and compute a specific optimum C/V ratio. Such automated detection, analysis, and prompting might reasonably move today's resuscitation research from the laboratory bench to the victim's side in the field. It also may allow for implementation of more complex guidelines for ventilation than would be easily remembered by most potential rescuers.

3.1 Limitations of the present study

The present study is obviously a theoretical one, based upon relatively simple geometric scaling rules. For purposes of simplicity, we assumed that a person maintains essentially the same shape, as he or she grows older. The classical developmental differences in proportions of human head size, to torso size, to leg length were assumed to be of limited importance from a metabolic standpoint during CPR. In addition, the proper scaling rule for basal metabolic rate and cardiac output for individuals of the same species remains somewhat controversial[16, 17]. The correct exponent may be 0.5, as suggested here, or perhaps greater or less than this value. Hence, there is room for error in our calculations. However, the sensitivity analysis presented in Figure 2 illustrates that the major conclusions of our study hold over a wide range of reasonable assumptions used to derive the exponent in the final scaling rule for the C/V ratio.

For simplicity and because the physiology and measurement of systemic oxygen delivery is already established for children, optimal C/V ratio is defined here in terms of systemic oxygen delivery. We make the assumption that optimal systemic oxygen delivery will parallel optimal myocardial or cerebral oxygen delivery during CPR, although there are circumstances where blood flows to these organ systems are dissociated. In the future, as measurements and information about the physiology of blood flow to various organs during pediatric CPR emerges, the current formulas may be adapted to calculate C/V ratios and optimize blood flow to targeted vascular beds.

An alternative to such a theoretical analysis, of course, would be an analysis of extensive experimental studies. However, there is also much room for error in experimental studies of optimization in CPR. Whether conducted in chaotic clinical environments or in more controlled laboratory environments, any such studies are prone to instability and deterioration of the subjects during periods of cardiac arrest. The resultant changes in biochemistry, physiology, and anatomy can be quite profound when a large number of repeated trials are done to find an optimal value for a particular parameter. Many such experiments would be needed for many subjects ranging from about 5 kg to 50 kg in body weight. Even in a well controlled laboratory setting with minimal arrest and resuscitation times[28], curve fitting and mathematical models are still needed to solve an optimization problem. The present theoretical approach, based upon accepted principles of anatomy and physiology, is probably as valid as any.

4. Conclusions

With the caveats appropriate for any idealized mathematical analysis, scaling of the Babbs-Kern formula for individuals of similar shape and differing body size (children vs. adults) suggests that the optimal C/V ratios for children must be different from that for adults. The "5 + one half age in years" rule for professional rescuers and the "5 + age in years" rule for lay rescuers provide a practical and simple, yet evidence-based titration of CPR interventions to the individual victim across the developmental spectrum. The effects of developmental anatomy and physiology, as predicted by simple estimates of age and body size, should be considered seriously in creating future guidelines for CPR in children.

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