Resuscitation 92 (2015) 148–153

Contents lists available at ScienceDirect

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Clinical paper

Generation of tidal volume via gentle chest pressure in children over one year old☆,☆☆

Ban C.H. Tsui*, Sara Horne, Jenkin Tsui, Gareth N. Corry

Department of Anesthesiology and Pain Medicine, University of Alberta, Edmonton, Alberta, Canada

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form 19 February 2015
Accepted 24 February 2015

Keywords:
Chest compressions
Resuscitation
Non-invasive oxygenation
Children

ABSTRACT

Background: In the event of cardiac arrest, cardiopulmonary resuscitation (CPR) is a well-established technique to maintain oxygenation of tissues and organs until medical equipment and staff are available. During CPR, chest compressions help circulate blood and have been shown in animal models to be a means of short-term oxygenation. In this study, we tested whether gentle chest pressure can generate meaningful tidal volume in paediatric subjects.
Methods: This prospective cohort pilot study recruited children under the age of 17 years and undergoing any surgery requiring general anaesthetic and endotracheal intubation. After induction of general anaesthesia, tidal volumes were obtained before and after intubation by applying a downward force on the chest which was not greater than the patient's weight. Mean tidal volumes were compared for unprotected versus protected airway and for type of surgery.
Results: Mean tidal volume generated with an unprotected and protected airway was 2.7 (1.7) and 2.9 (2.3) mL/kg, respectively. Mean tidal volume generated with mechanical ventilation was 13.6 (4.9) mL/kg. No statistical significance was found when comparing tidal volumes generated with an unprotected or protected airway ($p = 0.20$), type of surgery (tonsillectomy and/or adenoidectomy versus other surgery) (unprotected, $p = 0.09$; protected, $p = 0.37$), and when age difference between groups was taken into account ($p = 0.34$).
Conclusions: Using gentle chest pressure, we were able to generate over 20% of the tidal volume achieved with mechanical ventilation. Our results suggest that gentle chest pressure may be a means to support temporary airflow in children.

1. Introduction

Current cardiopulmonary resuscitation (CPR) guidelines suggest a Circulation-Airway-Breathing (C-A-B) sequence on unresponsive victims of cardiac arrest.[1] The circulation component involves downward compressions on the chest to restore and maintain blood circulation. Although still controversial, chest compressions alone have been suggested to be as effective for resuscitation as conventional, three-part CPR in adults. In fact, the American Heart Association (AHA) recommends Hands-Only™ CPR[2] be used for teens and adults who collapse suddenly in an "out-of-hospital" environment. Studies in animal models have shown that chest compression CPR can be as effective as combined ventilation and compression.[3–6] Moreover, several randomized clinical trials have shown that continuous chest compression CPR and conventional CPR have similar outcomes with respect to survival.[7–9]

Although supporting evidence is limited, it is theoretically possible that CPR chest compressions have ventilatory as well as circulatory benefits. During inspiration, the vertical dimension of the chest cavity is increased,[10] generating negative pressure in the intrapleural space and resulting in lung inflation. Once the intrathoracic pressure increases above atmospheric pressure, air flows out of the lungs according to the pressure gradient, and exhalation occurs. Application and release of chest pressure creates passive ventilation by generating supra-atmospheric and negative intrathoracic pressures, respectively. Air is thus forced from the lungs with the application of chest pressure (Fig. 1A) and drawn into the lungs as the chest wall recoils passively upon release of pressure

☆ A Spanish translated version of the abstract of this article appears as Appendix in the final online version at http://dx.doi.org/10.1016/j.resuscitation.2015.02.021.
☆☆ Clinicaltrials.gov identifier NCT01394172.

* Corresponding author at: 8–120 Clinical Sciences Building, University of Alberta, Edmonton, Alberta, Canada T6G 2G3.
E-mail address: btsui@ualberta.ca (B.C.H. Tsui).

http://dx.doi.org/10.1016/j.resuscitation.2015.02.021
0300-9572/

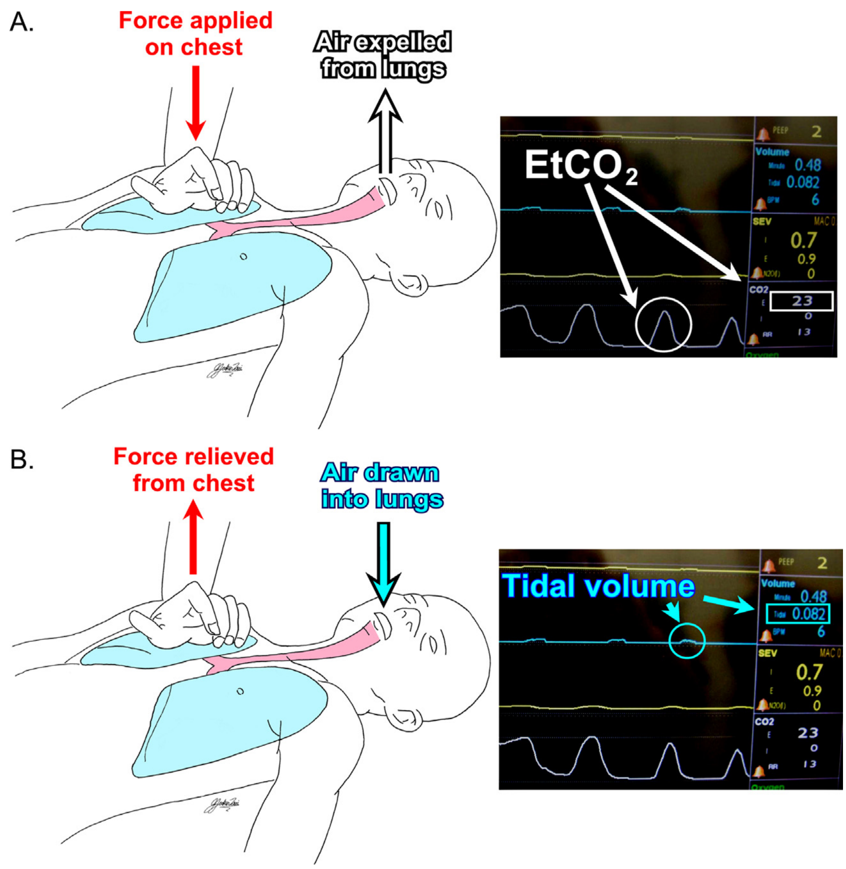

Fig. 1. (A) Schematic drawing of chest pressure ventilation technique showing position of hand on the chest and direction of air upon applying force to the chest. Inset, photograph of monitor showing end-tidal CO_2 ($EtCO_2$) generated with chest pressure ventilation technique. (B) Schematic drawing of chest pressure ventilation technique showing generation of tidal volume upon release of pressure from the chest. Inset, photograph of monitor showing tidal volume generated with chest pressure ventilation technique.

(Fig. 1B). This may be especially beneficial in children since their rib cages are more pliable than adults'. In this study, we assessed whether application of gentle chest pressure and subsequent chest recoil can generate tidal volume (TV) in paediatric subjects.

2. Patients and methods

This was a prospective cohort pilot study. Ethics approval was provided by the University of Alberta Health Research Ethics Board (approval reference #Pro00018804). Inclusion criteria were all paediatric patients (ASA I–III) under the age of 17 years who were undergoing elective surgery requiring a general anaesthetic with an endotracheal tube. Exclusion criteria were the following: failure to obtain parental consent or patient assent when appropriate (in general, children over 6 years of age), patients with any cardiac and/or respiratory pathology, and patients with any chest deformity (for example, pectus excavatum, pectus carinatum, or scoliosis).

2.1. Part A: TV with unprotected airway

Immediately after induction of a standard general anaesthesia (induction technique and decision to administer muscle relaxants was at the discretion of each individual anaesthesiologist responsible for the case), the patient was ventilated with a conventional "bag-and-mask" with 100% oxygen for 30 s. After ensuring the patient was in an apnoeic state, the mask was held over the patient's face and without any airway support devices (e.g., oropharyngeal/nasopharyngeal airway) or techniques (e.g., jaw thrust). Gentle pressure was then applied vertically down on the right chest specifically to avoid cardiac compressions (Fig. 1). The force applied was measured with a transducer (Lafayette Manual Muscle Testing System Model LA-01163, Lafayette, IN, USA) so as not to exceed the patient's actual weight. The downward and upward components of each compression lasted approximately 4 s, and the entire manoeuvre (three compressions) lasted a total of approximately 15 s with 1 s in between compressions.

Tidal volumes generated upon release of pressure on the chest were measured by the spirometry function of the anaesthetic machine (Primus, Drager Medical GmbH, Lubeck, Germany). The minimum detectable volume to trigger the spirometry function of the ventilator was also calibrated. Oxygen saturation was monitored continuously, and, if at any stage the oxygen saturation fell below 95%, the study protocol dictated that the anaesthesiologist return to "bag-and-mask" ventilation. Conventionally, saturations above 90% are considered to provide adequate oxygenation[11]; hence, there is a large safety margin built into the study protocol.

2.2. Part B: TV with protected airway

After measuring TV with an unprotected airway, the patient was ventilated manually with a bag and mask. A suitable size and length endotracheal tube (cuffed or uncuffed, depending on the anaesthesiologist's preference) was inserted into the trachea. With the endotracheal tube in place, positive ventilation was applied to confirm successful proper intubation with bilateral lung inflation. Once satisfactory endotracheal placement was confirmed, the chest pressure manoeuvre was repeated as described in Part A.

Table 1
Demographic data of study subjects organized by age category.

	Infant (>1–12 months) *n* = 7	Toddler (>1–3 years) *n* = 17	Child (>3–8 years) *n* = 43	Pre-teen (>8–13 years) *n* = 31	Adolescent (>13 years) *n* = 17
Gender (M/F)	5/2	12/5	19/24	16/15	6/11
Age (months)[a]	7.9 (2.3)	21.2 (5.4)	63.2 (14.6)	122.9 (17.8)	183.6 (17.0)
Weight (kg)[a]	8.6 (1.5)	11.9 (1.3)	21.7 (6.4)	40.7 (15.1)	66.7 (25.2)

[a] Values are mean (SD).

2.3. Part C: baseline TV with protected airway under 15 cm H_2O positive ventilation

Upon completion of Part B, ventilation was established using 15 cm H_2O positive ventilation. Tidal volume measurements were recorded and used as a baseline for comparison to TVs generated by gentle chest pressure.

2.4. Statistical analysis

A convenience sample of 100 patients was chosen. As this was a feasibility study, the sample size was not powered to detect any between-groups differences. We stratified the subjects according to age group: neonate (0–28 days or 44 post-conceptual weeks), infant (>1–12 months), toddler (>12 months–3 years old), small child (>3–8 years old), pre-teen (>8–13 years old), or adolescent (>13 years old). Feasibility data, including demographic details of the patients (age, weight, height, ASA status, any medical conditions) and type of surgery were recorded. The mean of the three clinical TV measurements were analyzed.

Using SPSS (version 20) (IBM, Armonk, NY) and MS Excel (Microsoft, Redmond, WA), analyses of variance were used to detect significant difference among age of patient population in respect to the mean TV generated. Mean TVs were tested for unprotected versus protected airway as well as for indication for surgery; that is, patients undergoing tonsillectomy and/or adenoidectomy (T/A) were compared to patients receiving other surgeries since T/A patients often have upper airway obstruction. A p value of <0.05 indicated a statistically significant difference. Regression analysis was performed in MS Excel.

3. Results

The minimum detectable volume to trigger the spirometry function of the ventilator was calibrated and determined to be 15 mL. Any volume injected below this value was incapable of triggering the spirometry function of the ventilator to provide a reading.

Following informed written consent, 116 patients were enrolled in the study. One neonate was excluded from data analysis because the TVs generated were likely below the minimum recordable volume of 15 mL (see above). Demographic data are shown in Table 1. Of the surgeries performed on our cohort, 44 (38%) were T/A, 28 (24%) were other otolaryngological procedures, 22 (19%) were dental surgeries, 12 (10%) were urologic surgeries, 5 (4%) were ophthalmologic procedures, and 4 (3%) were other surgeries. We observed no spontaneous breathing efforts in any of the subjects under general anaesthesia. In no patients did oxygen saturation values fall below 95%.

The mean force applied in both the unprotected and protected airway groups was 0.16 kg per kg patient weight. Table 2 shows the TVs generated for each age group under each condition (unprotected versus protected airway and with mechanical ventilation). No statistical significance was found when comparing TVs generated with an unprotected and protected airway ($p = 0.20$) or when the age difference between groups was taken into account ($p = 0.34$). Fig. 2 shows TV values generated for each subject from whom readings could be obtained compared to total anatomic dead space values calculated based on age, as described by Numa and Newth.[12] Data in Table 3 show no significant difference in TV generation when T/A patients were compared to those undergoing other surgeries (unprotected, $p = 0.09$; protected, $p = 0.37$).

One infant (0.9%) who underwent excess lip removal surgery, had TV readings of zero with both an unprotected and protected airway. Seven patients (6%), five of which underwent T/A surgery, had TV readings of zero before intubation. One patient (0.9%), an infant who underwent urologic surgery, had a TV reading of zero after intubation. When comparing TV generation with an unprotected versus protected airway among all patients, the incidence of a TV reading of zero approached but did not reach significance when comparing the groups ($p = 0.05$). When comparing the incidence of TV readings of zero among patients who underwent T/A surgery versus all other surgeries, we observed no significant difference with protected airways ($p = 0.16$) (Table 4). When comparing unprotected airways, the difference approached but did not reach significance ($p = 0.06$).

4. Discussion

Our main findings are that application of gentle chest pressure in anesthetized children resulted in 2.8+/−0.3 mL/kg TV with a natural airway and 3.2+/−0.4 mL/kg with an endotracheal tube in place. Although the mean TVs did not differ in the two groups,

Table 2
Tidal volumes generated for each age group with unprotected and protected airway and with mechanical ventilation.

Age group	Mean tidal volume (mL/kg) (95% CI)		
	Unprotected airway	Protected airway	Mechanical ventilation
Infant (*n* = 7)	2.4 (0.8–4.0)	2.0 (0.4–3.6)	15.2 (8.9–21.5)
Toddler (*n* = 17)	3.2 (2.7–3.7)	3.3 (2.7–3.9)	15.3 (13.5–17.2)
Child (*n* = 43)	3.1 (2.5–3.7)	4.0 (3.0–5.0)	13.7 (12.2–15.2)
Pre-teen (*n* = 31)	2.6 (2.0–3.2)	2.7 (2.2–3.2)	12.5 (10.9–14.2)
Adolescent (*n* = 17)	2.1 (1.4–2.8)	2.5 (2.1–2.9)	11.2 (9.6–12.8)
Mean	2.8 (2.5–3.1)	3.2 (2.7–3.6)[†]	13.3 (12.4–14.2)
Overall% TV generated (CPV/MV)	21%	24%	–

[†] $p = 0.20$, unprotected versus protected airway.

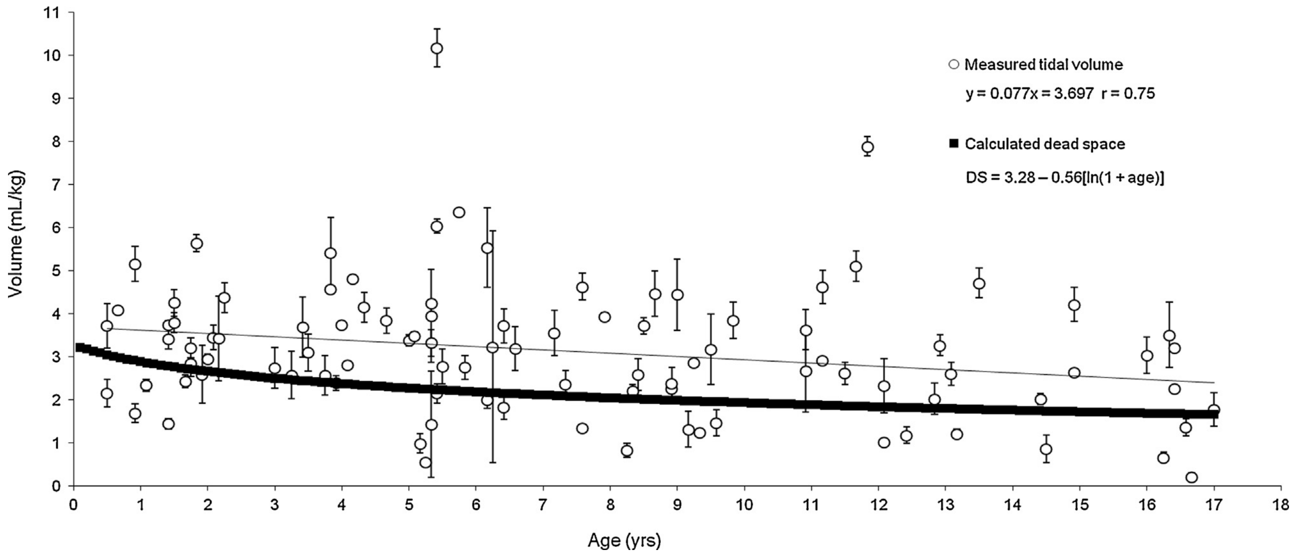

Fig. 2. Comparison of measured tidal volumes generated with gentle chest pressure and calculated anatomic dead space for children aged 1–17. Open circles represent mean tidal volumes for each study subject with measurable values; error bars indicate standard deviation for the same subject, and a best-fit curve is included for the tidal volume data. The thick line represents dead space values for each age between 0.1 and 17 years, calculated according to Numa and Newth[12] (see equation in top right corner).

Table 3
Mean tidal volumes generated in patients receiving tonsillectomy/adenoidectomy surgery versus other surgeries.

Surgery type	Mean tidal volume (mL/kg) (95% CI)		
	Unprotected airway	Protected airway	Mechanical ventilation
Tonsillectomy/adenoidectomy (*n* = 44)	2.4 (1.9–3.0)	3.0 (2.3–3.6)	12.0 (10.7–13.4)
Other surgeries (*n* = 71)	3.0 (2.6–3.4)[†]	3.4 (1.8–2.9)[‡]	14.1 (13.0–15.3)

[†] $p = 0.09$, T/A versus other surgeries (unprotected airway).
[‡] $p = 0.37$, T/A versus other surgeries (protected airway).

we noted a higher frequency of compressions with gas exchange below the threshold of measurement in the natural airway group. More importantly, these data suggest that the greater force provided during CPR may result in even greater TVs.

In children, compression-only CPR has only been shown to be as effective as conventional CPR (i.e., with rescue breaths) in cases of cardiac arrest with cardiac causes.[13] Although no direct evidence exists, these observations imply that chest compressions, in addition to restoring circulation, may provide some degree of oxygenation via a mechanism similar to the gentle chest pressure method used in this study. Reassuringly, the overall mean TV we generated with an unprotected airway was 2.8 mL/kg – higher than the total dead space reported for infants and children (1.0–1.96 mL/kg)[12] and slightly less than half the TV attained with normal breathing (5–7 mL/kg). Although the gentle chest compressions provided some airflow, our data offer no direct evidence as to whether sustained ventilation can be achieved with this technique. Further study is needed to demonstrate the merits of chest pressure or compressions in providing oxygenation in a clinical setting, where most patients already have oxygen and gas volumes depleted in their lung reservoir.

Table 4
Incidence of tidal volumes of zero in patients receiving tonsillectomy/adenoidectomy surgery versus other surgeries.

Surgery type	Tidal volume readings of zero (% of patients)	
	Unprotected airway	Protected airway
Tonsillectomy/adenoidectomy (*n* = 44)	6/44 (13.6%)	0/44 (0%)
Other surgeries (*n* = 71)	2/71 (2.8%)[†]	2/71 (2.8%)[‡]

[†] $p = 0.06$, T/A versus other surgeries (unprotected airway).
[‡] $p = 0.16$, T/A versus other surgeries (protected airway).

In this study, the maximum force applied to the chest wall was equivalent to the patient's body weight. This was done to limit the risk of injury from pressure on the chest. Application of force and pressure on the chest has been used to measure maximum expiratory volumes in neonates without adverse effects.[14] Additionally, a recent study simulating the effects of applying pressure on the chest to depress one third of the antero-posterior diameter suggested no adverse outcomes in patients between 3 months and 8 years old.[15] Although we could not find data describing chest compression force in younger children, our results show that the force applied to patients in the pre-teen and adolescent groups (>8 years old) (~6.0 kg) in our study was considerably lower than the force used in studies of children of a similar age (mean >30 kg).[16,17]

Our results are comparable with those of a previous study which used a porcine model to examine effectiveness of chest compressions for ventilation under conditions of continuous positive airway pressure (CPAP).[5] In their study, Hevesi et al. demonstrated that, with CPAP set to 75% of the animals' baseline ventilation, chest compressions allowed substantial CO_2 exchange and significantly higher SaO_2 levels compared to non-CPAP conditions. In contrast, our study was completely dependent on chest recoil following compression to draw in air (i.e., no CPAP). It is possible that the more effective ventilation seen in the Hevesi et al. study might be due in part to the enhancement of recoil properties by

CPAP. Nevertheless, we were able to demonstrate generation of TV without any additional ventilation equipment. Future studies with human subjects using CPAP combined with chest compressions may be able to achieve more effective generation of TVs.

An obstructed airway is expected to interfere with resuscitation following cardiac arrest. We anticipated that patients undergoing T/A surgeries would experience more incidence of upper airway obstruction. We found no significant difference in generated TV between these patients and those undergoing other surgeries, regardless of intubation status (Table 3). However, the overall incidence of TVs of zero with an unprotected airway was more frequent with T/A patients (6/44; 13.6%) compared to non-T/A patients (2/71; 2.8%) ($p = 0.06$) (Table 4). These observations suggest that the potential problems associated with inflamed oropharyngeal tissues do not significantly affect the ability to generate TV with either an unprotected or protected airway, a significant difference may have been observed with a larger sample size.

In this study, our ventilator was unable to obtain a TV reading below 15 mL. Multiple factors contribute to difficulties in measuring TV accurately at the expiratory valve of a conventional ventilator, including compensation for volume loss because of circuit and humidifier compliance, temperature changes, humidification, and presence of secretions. In contrast, measuring TV at the airway opening overcomes most circuit compliance and dead space factors.[19] Since the majority of ventilators calculate TV at the ventilator level, verification of circuit compliance is an important element in determining TV. There are several ways to assess tubing compliance, and since its value depends on compressibility of the gas, tubing compliance can vary depending on the method of measurement. Indeed, some studies have shown that, if circuit compliance is obtained using the same flow rates as those used in mechanical ventilation, actual TVs can be estimated with measurements at the ventilator level.[20] In our study, the data from a neonatal patient were excluded from further analysis since it was uncertain whether the TV reading was below the 15 mL threshold or actually zero. In future studies, equipment that is sensitive enough to detect small volumes will be needed to assess generation of TV via gentle chest pressure in neonates.

One important limitation of this study is that the chest pressure applied – both in force and frequency – was not representative of standard CPR compressions, and, therefore, the two techniques cannot be compared directly. However, our objective was not to test CPR-type compressions; rather we wished to demonstrate that gentle pressure on the chest would generate airflow as determined by tidal volume measurement. Another limitation of this study is that only three TV measurements were collected for analysis, all within the time of initial induction of anaesthesia. This was primarily due to balancing the time needed to perform the study while maintaining operating room efficiency. In terms of generating TV with gentle chest pressure (including chest compressions), it therefore remains to be determined how sustainable this method is in providing oxygenation over longer periods of time (i.e., until ventilation equipment is available). A third limitation of the study is that we did not account for dead space in the tubing and equipment when taking TV measurements. Instead of measuring flow directly, we relied on the difference between before-and-after measurements detected by the ventilator. A fourth potential limitation of the study is that we did not attempt to assess for leaks around the endotracheal tube. Most of the time, uncuffed tubes were used; if a cuffed tube was used, it was not inflated as per routine practice at our institution when intubating paediatric patients.

5. Conclusions

In summary, this is the first study demonstrating that TV can be generated upon release of gentle pressure applied to the chest in paediatric patents. Our results help to shed light on the resuscitative property of chest compressions during CPR and suggest that, at least in children, chest pressure may facilitate temporary oxygenation in addition to restoring circulation. Our findings are also supported by studies showing that, in some circumstances, chest compression-only CPR is as beneficial as CPR with compressions and rescue breaths. Despite our encouraging observations, further research is required to demonstrate the ability of chest pressure or compressions to provide clinically relevant oxygenation.

Conflicts of interest statement

The authors have no conflicts of interest to disclose.

Funding

Dr. Tsui is supported by a Clinical Scholar Award from the Alberta Heritage Foundation for Medical Research (AHFMR). Dr. Tsui's research is also supported by the Canadian Anesthesia Research Foundation.

Acknowledgements

The authors wish to thank Zakiya Dhanani, Dr. Vivian Ip, and Dr. Allan de Caen for their contributions to the study and manuscript. The authors also thank their paediatric anaesthesiology colleagues at the Stollery Children's Hospital for their support in using gentle chest pressure for selected paediatric cases.

References

1. Field JM, Hazinski MF, Sayre MR, et al. Part 1: Executive summary: 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. Circulation 2010;122:S640–56.
2. Sayre MR, Berg RA, Cave DM, et al. Hands-only (compression-only) cardiopulmonary resuscitation: a call to action for bystander response to adults who experience out-of-hospital sudden cardiac arrest: a science advisory for the public from the American Heart Association Emergency Cardiovascular Care Committee. Circulation 2008;117:2162–7.
3. Berg RA, Kern KB, Hilwig RW, et al. Assisted ventilation does not improve outcome in a porcine model of single-rescuer bystander cardiopulmonary resuscitation. Circulation 1997;95:1635–41.
4. Chandra NC, Gruben KG, Tsitlik JE, et al. Observations of ventilation during resuscitation in a canine model. Circulation 1994;90:3070–5.
5. Hevesi ZG, Thrush DN, Downs JB, Smith RA. Cardiopulmonary resuscitation: effect of CPAP on gas exchange during chest compressions. Anesthesiology 1999;90:1078–83.
6. Kern KB, Hilwig RW, Berg RA, et al. Importance of continuous chest compressions during cardiopulmonary resuscitation: improved outcome during a simulated single lay-rescuer scenario. Circulation 2002;105:645–9.
7. Hallstrom A, Cobb L, Johnson E, Copass M. Cardiopulmonary resuscitation by chest compression alone or with mouth-to-mouth ventilation. N Engl J Med 2000;342:1546–53.
8. Rea TD, Fahrenbruch C, Culley L, et al. CPR with chest compression alone or with rescue breathing. N Engl J Med 2010;363:423–33.
9. Svensson L, Bohm K, Castren M, et al. Compression-only CPR or standard CPR in out-of-hospital cardiac arrest. N Engl J Med 2010;363:434–42.
10. West JB. Respiratory physiology: the essentials. 8th ed. Philadelphia: Lippincott Williams & Wilkins; 2008.
11. Williams AJ. ABC of oxygen: assessing and interpreting arterial blood gases and acid–base balance. BMJ 1998;317:1213–6.
12. Numa AH, Newth CJ. Anatomic dead space in infants and children. J Appl Physiol (1985) 1996;80:1485–9.
13. Kitamura T, Iwami T, Kawamura T, et al. Conventional and chest-compression-only cardiopulmonary resuscitation by bystanders for children who have out-of-hospital cardiac arrests: a prospective, nationwide, population-based cohort study. Lancet 2010;375:1347–54.
14. Adler SM, Wohl ME. Flow-volume relationship at low lung volumes in healthy term newborn infants. Pediatrics 1978;61:636–40.
15. Braga MS, Dominguez TE, Pollock AN, et al. Estimation of optimal CPR chest compression depth in children by using computer tomography. Pediatrics 2009;124:e69–74.

16. Maltese MR, Castner T, Niles D, et al. Methods for determining pediatric thoracic force-deflection characteristics from cardiopulmonary resuscitation. Stapp Car Crash J 2008;52:83–105.
17. Niles DE, Nishisaki A, Sutton RM, et al. Comparison of relative and actual chest compression depths during cardiac arrest in children, adolescents, and young adults. Resuscitation 2012;83:320–6.
19. Heulitt MJ, Holt SJ, Thurman TL, et al. Reliability of measured tidal volume in mechanically ventilated young pigs with normal lungs. Intensiv Care Med 2005;31:1255–61.
20. Silvestri S. The influence of flow rate on breathing circuit compliance and tidal volume delivered to patients in mechanical ventilation. Physiol Meas 2006;27:23–33.