Alternative ventilation strategies in cardiopulmonary resuscitation

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The introduction of the 2000 Guidelines for Cardiopulmonary Resuscitation emphasizes a new, evidence-based approach to the science of ventilation during cardiopulmonary resuscitation (CPR). New laboratory and clinical science underemphasizes the role of ventilation immediately after a dysrhythmic cardiac arrest (arrest primarily resulting from a cardiovascular event, such as ventricular defibrillation or asystole). However, the classic airway patency, breathing, and circulation (ABC) CPR sequence remains a fundamental factor for the immediate survival and neurologic outcome of patients after asphyxial cardiac arrest (cardiac arrest primarily resulting from respiratory arrest). The hidden danger of ventilation of the unprotected airway during cardiac arrest either by mouth-to-mouth or by mask can be minimized by applying ventilation techniques that decrease stomach gas insufflation. This goal can be achieved by decreasing peak inspiratory flow rate, increasing inspiratory time, and decreasing tidal volume to approximately 5 to 7 mL/kg, if oxygen is available. Laboratory and clinical evidence recently supported the important role of alternative airway devices to mask ventilation and endotracheal intubation in the chain of survival. In particular, the laryngeal mask airway and esophageal Combitube proved to be effective alternatives in providing oxygenation and ventilation to the patient in cardiac arrest in the prehospital arena in North America. Prompt recognition of supraglottic obstruction of the airway is fundamental for the management of patients in cardiac arrest when ventilation and oxygenation cannot be provided by conventional methods. "Minimally invasive" cricothyroidotomy devices are now available for the professional health care provider who is not proficient or comfortable with performing an emergency surgical tracheotomy or cricothyroidotomy. Finally, a recent device that affects the relative influence of positive pressure ventilation on the hemodynamics during cardiac arrest has been introduced, the inspiratory impedance threshold valve, with the goal of maximizing coronary and cerebral perfusion while performing CPR. Although the role of this alternative ventilatory methodology in CPR is rapidly being established, we cannot overemphasize the need for proper training to minimize complications and maximize the efficacy of these new devices. Curr Opin Crit Care 2002, 8:199–211

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Abbreviations

AHA	American Heart Association
BLS	basic life support
BVM	bag-valve-mask
COPA	cuffed oropharyngeal airway
CPAP	continuous positive airway pressure
CPR	cardiopulmonary resuscitation
ERC	European Resuscitation Council
LMA	laryngeal mask airway
PTL	pharyngotracheal lumen airway

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Since the pioneers of modern cardiopulmonary resuscitation (CPR) introduced the airway patency, breathing, and circulation (ABC) sequence in the 1960s, many lives have been salvaged [1]. In the 1960s, three essential phases of CPR—closed chest cardiac massage, electrical defibrillation, and artificial ventilation—when properly combined, were recognized as being able to reverse death from cardiorespiratory arrest. Although the primary purpose of CPR is clearly to restore oxygenation and to remove carbon dioxide from the tissues once circulation is regained, the relative importance of ventilation during CPR has recently been re-evaluated, and alternative ventilatory methodologies in CPR have been studied. In this report, we will review new thoughts and considerations on traditional noninvasive and invasive techniques of manipulation management of the airway as well as the development of new approaches to emergency airway management in light of the new, evidence-based science reviewed by the Guidelines 2000 for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care [2].

Is no ventilation an alternative?

Dysrhythmic cardiac arrest

At the end of 2001, a panel of resuscitation experts summarized current recommendations for the Action Sequence for the Layperson during Cardiopulmonary Resuscitation [3•]. Briefly, the group concluded that the current status of knowledge in CPR underemphasizes the need for ventilation in the immediate period after cardiac arrest. How was this conclusion reached? Evidence-

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based medical data on this issue have been accumulating over the past decade, both in animal and human studies.

In the early 1990s, studies using a canine ventricular defibrillation model showed that when cardiac arrest was treated only with chest compressions, without active ventilation, the average arterial blood saturation was maintained at about 70% for up to 10 minutes during CPR [4]. More experimental work followed at the Critical Care Institute in Palm Springs, Florida, and the University of Arizona, showing that large animal survival and neurologic outcome up to 48 hours were not different when ventilation was withheld during resuscitation. These initial studies, although clearly de-emphasizing the importance of ventilation during the first few minutes of CPR, were limited by the persistence of an "artificial" patent airway in the animal, which resulted from the presence of an endotracheal tube allowing exchange of ventilations from gasping and chest compressions/decompressions [5,6]. Furthermore, these initial observations could not be verified by a different group of investigators [7].

More recent studies eliminated the possible influence of an artificial patent airway in animal models during CPR. When standard CPR was compared with compression-only CPR in a pig model in which the airway was occluded, no difference was found in 24-hour outcome [8]. It is important to note that a supine, unconscious dog or pig usually has a patent airway, whereas a supine, unconscious human has an obstructed airway resulting from the kinked nature of the human airway. These model differences are rarely discerned in CPR ventilation experiments but do have fundamental clinical importance. These latest observations confirmed that ventilation for a few minutes after dysrhythmic cardiac arrest was not fundamental and suggested the need to test the no-ventilation hypothesis in humans [9].

In a prospective, observational study of CPR and ventilation, chest compression–only CPR, and no CPR, survival from CPR (*ie*, return of spontaneous circulation) was found to be 16%, 15%, and 6% respectively [10]. Although both forms of basic life support (BLS) were significantly better than no CPR, there were no differences between CPR with or without ventilation. Similar results were reported more recently in North America in a study of telephone dispatcher–assisted BLS-CPR in which survival of compression-only CPR versus ventilation CPR was 14% versus 10%, respectively, with a slight trend of survival favoring chest compression–only CPR [11]. Although this study emphasized that CPR without ventilation is better than nothing, it presents several limitations in design. Mouth-to-mouth ventilation performed by a bystander was assessed by emergency medicine dispatcher only and not by the investigator at the scene; the patency of the airway was unclear in some patients, and primary respiratory arrests were excluded. In addition, if the bystander knew how to perform CPR, then the patient was excluded from the study. Nevertheless, the study suggested a need to reconsider BLS with a goal of minimizing the time to onset of CPR in the cardiac arrest victim and maximizing the efficacy of chest compression. When the concept of this "simplified CPR" was tested in a mannequin, effective compression was achieved an average of 30 seconds earlier than with the standard technique, and the number of compressions per minute were approximately doubled [12].

Despite the overall enthusiasm for the relatively positive results of dispatcher-assisted CPR instructions without ventilation as described by the providers [10,11], it has been emphasized by independent observers that the concept of no-ventilation CPR could be a misnomer, because, provided that the airway is open, patients undergoing ventricular defibrillation often exchange a significant amount of air through gasping [13]. Therefore, the term "CPR without assisted ventilation" has been suggested. Although the North American literature seems to underemphasize the importance of ventilation in the first few minutes after cardiac arrest, a recent Swedish report of 14,000 patients showed increased survival to 1 month for "complete CPR" (both chest compressions and ventilation) versus "incomplete CPR" (compression only) (survival, 9.7% *vs* 5.1%; $P < 0.001$) [14••]. In this study, ventilation and duration of less than 2 minutes between patient collapse and the beginning of lay bystander CPR were both powerful modifying factors on survival at 30 days, emphasizing the need for better and earlier CPR.

The effect of tidal volume and gas composition when ventilation is used in CPR has recently been the subject of in-depth research. Although in the early 1950s original CPR case reports showed that mouth-to-mask and mouth-to-mouth ventilation were clearly beneficial [15], recent observations could not confirm this [16–18]. In fact, a study in a pig model of CPR showed that ventilation with air is advantageous compared with exhaled breath (16% to 17% of O_2 and 3.5% to 4% of CO_2), and that hypercarbia and hypoxia can each, independently, decrease the rate of return of spontaneous circulation [19]. Furthermore, when these gas concentrations were used in a swine model with 6–mL/kg ventilation, profound arterial desaturation was noted and was shortly followed by hemodynamic instability [18]. This instability and desaturation were not observed if the tidal volume was increased to 12 mL/kg, or if a fraction of inspired oxygen of 0.70 was used with a tidal volume of 6 mL/kg. Two main features make older human studies different from more recent animal laboratory experiences [15]: (1) the patients described in the original case reports were typically paralyzed, and (2) the rescuer hyperventilated to the point of feeling dizzy, an arterial partial pressure of carbon dioxide of about 20 mm Hg. These differences highlight the need for more controlled human studies before recommending withholding mouth-to-mouth ventilation during cardiac arrest.

Asphyxial cardiac arrest

Although recent evidence-based literature acknowledges the importance and efficacy of CPR without ventilation, the need for assisted ventilation in cardiac arrest with asphyxia (cardiac arrest primarily resulting from respiratory arrest) or in pediatric populations (generally younger than 8 y) cannot be overemphasized [3•]. Cardiac arrest with asphyxia was originally illustrated in the first case of external chest compressions [20]. The rationale of ventilation during CPR for cardiac arrest is based on the assumption that CPR delays brain death in no-flow situations, and that hypoxia and respiratory acidosis can aggravate the injury. A critical decrease of brain ATP of 25% below the normal level has been observed after 4 minutes in an animal model of decapitated normothermic dog [21].

In general, arterial partial pressure of oxygen is maintained within the normal range for approximately 1 minute in a dog model of chest compressions without ventilation [22]. Furthermore, when asphyxia is the cause of cardiac arrest, oxygen consumption has proceeded to near complete exhaustion, and carbon dioxide and lactate have significantly accumulated just before cardiac arrest. This is in contrast with ventricular fibrillation, in which hypoxemia and acidemia become significant only several minutes after the onset of cardiac arrest. In a model of resuscitation after asphyxia (clamping of the endotracheal tube in an anesthetized pig), the animal subjects were randomly selected to receive resuscitation with and without simulated mouth-to-mouth ventilation. Return of spontaneous circulation was noted only when ventilation was added to chest compression [23]. Successful chest compressions and mouth-to-mouth rescue breathing allowed complete neurologic recovery in 90% of the animals.

The presence of a foreign body obstructing the airway is an uncommon, but important, cause of cardiac arrest with asphyxia, with an incidence of 0.65 to 0.9 per 100,000 cardiac arrests [2]. A recent study seems to support the original investigation of Ruben and MacNaughton [24] that abdominal thrust is not necessary in foreign body choking, and that chest compressions can achieve higher airway pressure than the Heimlich maneuver [25]. In fact, when CPR was performed and compared with an abdominal thrust in the cadaver, median and peak airway pressure reached a value of 30 cm H_2O versus 18 cm H_2O and 41 cm H_2O versus 26 cm H_2O, respectively. Only in a moderately obese cadaver was the mean airway pressure produced by the Heimlich maneuver higher than that produced with chest compression. The European Resuscitation Council (ERC) has recently addressed acute asphyxia from airway obstruction [26••]. The ERC embraced most of the new American Heart Association (AHA) recommendations for ventilation of the unprotected airway during resuscitation—particularly the need for lower tidal volume during resuscitation when additional oxygen is available and increased tidal volume (800–1200 mL) when ventilation is provided (*ie*, bag-valve-mask [BVM] or mouth-to-mouth ventilation) without supplemental oxygen. However, the ERC recognized that the most important feature of the new guidelines are the recommendations to deliver each breath slowly (over approximately 2 s) to minimize peak inspiratory pressure with resultant gastric inflation. In Europe, more emphasis has been placed on simplifying techniques to provide aid to the choking unconscious victim; clarifying terms related to breathing patterns in the victim after resuscitation, particularly the difference between normal breathing and agonal respiration; and simplifying algorithms for better skill retention [27]. Despite recent knowledge that ventricular fibrillation in children may be higher than previously thought [28], asphyxia is the most common cause of cardiac arrest in the pediatric population. The Pediatric Resuscitation Subcommittee of the Emergency Cardiovascular Care Committee (AHA) worked with the Neonatal Resuscitation Program Steering Committee (American Academic of Pediatrics) and the Pediatric Working Group of the International Liaison Committee on Resuscitation to review recommendations on oxygenation and ventilation in neonatal resuscitation [29]. The approach to the recommendations has been the same as that described in the AHA Guidelines 2000 for adults, which use five classes of recommendations centered on evidence-based medical data. Up to 10% of newborn infants require resuscitation at birth. The majority, because of the presence of meconium airway obstruction/aspiration, require immediate intervention and assisted ventilation. Because of their unique physiology, the importance of ventilation/oxygenation in newborns cannot be overemphasized. Fluid-filled lungs and intra- as well as extracardiac shunts at birth are physiologically reversed in the first few minutes of extrauterine life with either spontaneous or assisted vigorous chest expansion. Failure to normalize this function may result in persistence of right-to-left, intra- and extracardiac shunt, pulmonary hypertension, and systemic cyanosis. Bradycardia usually follows, with severe hemodynamic instability and rapid deterioration to cardiac arrest. Although these physiologic characteristics are typical of the newborn (minutes to hours after birth), similar events can be triggered by hypoxia in neonates (first 28 days of life) and infants (12 months of age). The importance of proper ventilation/oxygenation and the small margin of safety resulting from the unique physiology and high oxygen consumption of the newborn mandate the need for immediate ventilation and the presence of skilled personnel at the bedside to perform proper basic steps of resuscitation. Clearance of meconium fluid should be the immediate maneuver performed upon birth and providing positive pressure ventilation should be considered within 30 seconds when bradycardia or apnea is present. Tracheal intubation remains the gold standard for providing immediate ventilation/oxygenation to the newborn. European and American guidelines have essentially the same sequence of resuscitative events in neonates, recommending a chest compression–to-ventilation ratio of 3 to 1, with about 90 compressions and 30 breaths per minute with emphasis on quality of ventilation and compressions [30••].

An important feature of an alternative airway to BVM ventilation during BLS in the pediatric population is the possibility to administer life-saving drugs through an alternative airway when an intravenous or intratracheal route is not available. A recent study showed that when epinephrine is used in the pharynx at a dosage 10-fold higher than the recommended dose for endotracheal application, the same level of blood catecholamine can be achieved, although the absorption is delayed because pharyngeal mucosa vasoconstriction may be possible [31].

In young patients up to 8 years old, the airway patency, breathing, and circulation approach to CPR sequencing was not modified. In fact, the importance of immediate, aggressive management of the airway and ventilation in this group of patients has been reaffirmed ("go fast 911" instead of "call first 911"). However, a proposal to extend the age limit of the "go fast" algorithms to ages beyond 30 years was found to be unjustified based on actual knowledge by an ad hoc committee [3•]. In conclusion, ventilation remains essential in cardiac arrest with asphyxia in both adult and pediatric patients.

Ventilation of the unprotected airway

Although securing the airway and endotracheal tube placement remain the gold standard for ventilation, oxygenation and suctioning of the airway in patients after cardiac arrest and mouth-to-mouth rescue breathing with exhaled gas or BVM ventilation can serve as quick and effective ways to provide oxygen to the victim. In both cases, the airway is unprotected from the risk of obstruction, regurgitation, and pulmonary aspiration.

It has been recognized for 50 years that upper airway obstruction occurs commonly in cardiac arrest victims as a result of loss of muscle tone, and that proper manual techniques to markedly reduce or prevent such obstruction are important [15]. In particular, prevention and treatment of upper airway obstruction by extending the neck and jaw and applying this in conjunction with mouth-to-mouth or mask ventilation has been taught by the same investigators as an essential in providing first aid to the victim of respiratory or cardiac arrest.

Mouth-to-mouth ventilation

In recent decades, a widespread fear of acquiring contagious diseases from victims of cardiac arrest has resulted in reluctance among the lay public, and even some health professionals, to perform mouth-to-mouth ventilation. Infectious disease concerns include *Helicobacter pylori*, *Salmonella*, *Herpes simplex* virus, tuberculosis, HIV, and the hepatitis [32–34].

Being repulsed by the sight of a victim in agony and the fear of doing harm may also affect the decision to provide mouth-to-mouth ventilation. Recent surveys of CPR instructors reported that all would perform mouth-to-mouth ventilation on a 4-year-old drowned child, but only 54% on a college student, 35% on a hemophiliac, 18% on a stranger in a bus in San Francisco, and 10% on a person who had overdosed on heroin [35–36].

Awareness of new infectious disease issues, if not new infectious diseases, has resulted in the current recommendation of the AHA to use barrier devices to protect the rescuer against contamination with any infective secretions [37]. Effective barriers against contamination increase efficacy and effectiveness of CPR, helping the rescuer to overcome the fear of contamination and to immediately start resuscitation. However, the overall willingness to perform bystander CPR is disappointingly low in the United States, Europe, and Japan, both for laypersons and health care providers alike. Different reasons are responsible for this widespread attitude. In the United States and Europe, the factor deterring performance of mouth-to-mouth ventilation by a bystander or health care provider is fear of contracting infectious diseases. This does not seem to be the case in Japan, where unwillingness to perform mouth-to-mouth ventilation is mostly a result of lack of confidence in one's ability to properly perform CPR [38]. The difference may be related to the 200-fold lower incidence of HIV in Japan, as compared with the United States [39].

Education and increased retention of proper mouth-to-mouth ventilation technique is fundamental but difficult to apply to all populations. The use of television spots as a means of teaching basic skills of CPR in at-risk populations has been explored in Brazil. Although television spots seem to increase skill retention over 1 year, mouth-to-mouth ventilation and effective external cardiac compression are recognized as skills that are dependent on supervised practice with mannequins. Although the study is limited, it makes sense to use an alternative methodology to promote resuscitation skills in the lay population, including the use of educational clips or scenarios in entertaining and motivating television spots [40].

The safety of ventilating the unprotected airway during cardiac arrest has been recently challenged based on new knowledge acquired about the pathophysiologic changes in airway resistance, respiratory system compliance, and the lower esophageal sphincter pressure shortly after cardiac arrest [41–45].

The origin of changes in lung resistance and compliance during CPR may be multifactorial. Pre-existing chronic obstructive lung disease, mucus, or bronchoconstriction can increase resistance. Pulmonary vascular congestion during cardiac arrest increases the volume of the parenchymal interstitium and decreases compliance. Chest compressions, pulmonary edema, and alveolar flooding resulting from cellular anoxia may also contribute to the observed changes in compliance [46]. These variables, added to correct ventilation techniques, determine gas distribution between the lungs and the esophagus and, subsequently, the stomach. Lower esophageal sphincter pressure is the pressure at the esophageal–gastric junction that prevents regurgitation of stomach contents into the pharynx and insufflation of air into the gastrointestinal tract during ventilation. The lower esophageal sphincter pressure in a healthy adult is approximately 20 to 25 cm H_2O. Animal investigations have shown that lower esophageal sphincter pressure deteriorates rapidly from a baseline level of 20 to 5 cm H_2O within 5 minutes of untreated cardiac arrest [42].

Both airway resistance and total lung compliance determine the gas distribution between lungs and stomach during ventilation via an unprotected airway. In general, the relation between peak inflation pressure and lower esophageal sphincter pressure is the primary determinant of the gas distribution between the stomach and lungs. When peak inflation pressure exceeds lower esophageal sphincter pressure, air will flow into the stomach. Immediate consequences include further reduction of the lung compliance and an increased risk of gastroesophageal regurgitation with pulmonary aspiration of gastric contents. Thus, effective ventilation strategy during cardiac arrest should aim to maintain the unprotected airway permanently patent and to keep peak inflation pressure minimal at all times to prevent stomach inflation. Correct alignment of the airway by chin support and backward tilt is very important during ventilation in the presence of an unprotected airway.

Effectiveness and safety of ventilation of the unprotected airway have been extensively studied in bench models. When a mechanical ventilator was used to provide a tidal volume of 500 mL and 1000 mL, respectively, in an *in vitro* model of an unprotected airway, significantly less stomach inflation was found when applying a smaller tidal volume (approximately 500 mL) with a mechanical ventilator compared with a tidal volume of approximately 1000 mL [47]. For the same reason, the use of a smaller, pediatric, self-inflating bag delivering a maximal volume of 500 mL showed less gastric inflation in the same model when compared with the large adult bag [18,48].

All of these studies suggest that when the peak airway pressure exceeds lower esophageal sphincter pressure during ventilation of an unprotected airway, the stomach is likely to be inflated. As a result, a tidal volume of 6 to 7 $mL{\cdot}kg^{-1}$ body weight (approximately 500 mL) and an inspiratory time of 1.2 to 2 seconds was recommended by the ERC in 1998 and, later, by the International Guidelines 2000 for CPR and Emergency Cardiovascular Care, as long as oxygen supplementation is available [2,49]

Better knowledge of hemodynamics and oximetry during CPR also support the use of smaller tidal volumes than previously taught. When cardiac output and pulmonary flow are extremely low (<30% of normal), carbon dioxide excretion is dependent more on cardiac output than on tidal volume and minute ventilation [50]. In a swine model of cardiac arrest and low flow rate controlled by a biventricular assist device, mixed venous blood gases reflected tissue oxygenation and acid-base state accurately [51].

Thus, in such circumstances, a tidal volume that is considerably lower than that required in the presence of a normal cardiac output may produce normal arterial blood gases and provide adequate exchange of alveolar gas during CPR. Although a tidal volume of 5 mL/kg in an unprotected airway in an animal model of cardiac arrest seems not to differ from a volume of 10 to 12 mL/kg in terms of achievement of arterial oxygen saturation, little information is known about carbon dioxide in this context.

A recent Norwegian study analyzed the carbon dioxide and pH of patients receiving tidal volumes of 500 mL versus 1000 mL several minutes after intubation during out-of-hospital cardiac arrest (mean time of approximately 15 min) [52]. Remarkably, normocapnia was not achieved in either tidal volume when frequency was maintained at 12 breaths per minute. However, pH and arterial partial pressure of carbon dioxide were statistically lower and higher, respectively, at both 5 minutes and 10 to 15 minutes between the two groups. This study cannot be compared with BLS manipulations of the unprotected airway because an endotracheal tube was always present, and variables such as gastric inflation, peak airway pressure, and effective tidal volume could be easily controlled. However, it raised the controversial issue of the best arterial blood gas to be achieved during CPR, because there is evidence in the literature that both arterial and myocardial hypercarbic acidosis can reduce cardiovascular stability and the ability of the heart to be resuscitated [19,50, 53–57].

In any case, it has been observed that, during cardiac arrest, arterial blood gas does not reflect tissue and that the mixed venous blood gas has a level of carbon dioxide that is frequently twice the level of the arterial side [50,51,57]. Cricoid pressure (Sellick maneuver) should always be applied when feasible to prevent stomach inflation, because it can effectively protect against gastric regurgitation with the limitation of the victim near cardiac arrest still actively vomiting, in whom the risk of esophageal rupture is rare but present [58].

Spontaneous breathing during cardiac arrest has been extensively investigated as an outcome variable. When spontaneous ventilation during CPR occurs and the patient's mouth is open, gasping will result. In this situation, mouth-to-mouth ventilation may not be necessary. The value of gasping during CPR in humans must be interpreted with caution because of fundamental differences in human and animal upper airway anatomy—straight in murine, porcine, and canine models but convoluted in humans and, therefore, subject to rapid occlusion by the tongue and soft tissue of the pharynx. In general, gasping can be observed by the bystander up to 50% of the time immediately after cardiac arrest and is more frequently present (27% *vs* 17%) if CPR is performed promptly versus after prolonged, unattended cardiac arrest [59,60]. In the absence of a dedicated airway, extending the head by placing a pillow under the shoulder or gently tilting the head laterally can reduce the acute pharyngeal obstruction that results from the tongue falling backward over the palate. The implications of these maneuvers in a patient with an unstable cervical spine are worrisome.

Bag-valve-mask ventilation

Proper mask ventilation is a fundamental skill of resuscitation and should receive a high priority in training of both adult and pediatric providers [61–62]. In general, BVM ventilation can be considered ventilation of the unprotected airway with the important modification that oxygen or at least room air is always available. The breath is delivered more efficiently by a high-volume bag (1.6 L) and a mask is applied to deliver the tidal volume. Therefore, the same pulmonary mechanics and CPR as reviewed in the BLS section of mouth-to-mouth ventilation can be applied to this technique of ventilation; this includes concerns about lower esophageal pressures and passive regurgitation in view of decreased pulmonary compliance during cardiac arrest.

Generally, a high-flow, fresh oxygen source allows better compensation for facemask leaks and generation of sufficient positive pressure to overcome respiratory system resistance to gas flow. Jaw thrust and neck extension is usually necessary to provide a patent airway. Proper seal of the facemask can be obtained by adjusting the cushion tension in adult facemasks. In many masks, the cushion inflation volume can be adjusted by adding or removing air with a syringe via a valve in the mask. The mask should be sized to cover the nose at the level of the nose bridge and the mouth just above the chin.

Particularly in obese patients, the combination of redundant oropharyngeal soft tissue, a bulky tongue, and a thick chin and neck pad may interfere with the ability to ventilate. Several methods may be used to overcome this resistance. Lifting the chin pad while applying a jaw thrust can straighten the soft tissues of the anterior wall in the hypopharynx and facilitate ventilation. Early insertion of a plastic oral airway or tilting the head laterally while ventilating may reduce the risk of the tongue falling backward against the soft palate. Finally, two-person mask ventilation may be more effective and should be attempted.

Various clinical signs may be noted during airway obstruction. Gas passing through an obstructed airway may generate a characteristic bubbling noise. Absence of chest movement or breath sounds appreciated from the precordial stethoscope also strongly suggests inadequate or absent ventilation.

The performance of the apparatus used to deliver BVM ventilation has recently been extensively reviewed. Seven commercially available models of ventilating bags used on an advanced cardiac life support training mannequin connected to an artificial lung in which compliance and resistance were set at normal have been evaluated with regard to the tidal volume provided [63]. Interestingly, standard ventilations with one hand averaged a tidal volume between 450 to 600 mL in both genders despite significant differences in the size of male and female hands. When the technique was modified to open palm and total squeezing of the self-inflating bag against the flexed rescuer's knee, next to the patient's head, total volume ranged from 888 to 1192 mL. This study seems to indicate that most of the commercially available ventilating bags can provide both the 5-mL/kg and 12-mL/kg volume ventilation, as recommended by the new BLS guidelines, with and without available oxygen in a reliable manner. However, this study was performed on a mannequin with normal compliance and resistance, and gastric inflation was not measured.

When ventilation is provided to a victim of cardiac arrest, proper tidal volume cannot be easily assessed. Excitement and overenthusiasm of the professional rescuer at the scene of cardiac arrest can increase the chance of unnecessary gastric inflation [64•]. In a recent, intriguing paper from Austria, it was shown that the stomach inflation of the victim, as assessed by postresuscitation chest radiograph, was minimal and statistically lower (15%) when the lay bystander provided mouth-to-mouth ventilation the stomach inflation versus when professional paramedics ventilated the victim with a BVM device [65•].

There are many possible explanations for these results, which are partially related to the limitation of the chest radiograph as a test to assess gastric inflation and the lack of autopsy reports from the nonsurviving victims. However, it is also possible that "extreme efficiency" of ventilation by the paramedics as compared with the bystander's mouth-to-mouth ventilation determined the difference. This finding, combined with the observation that professional rescuers tend to squeeze the bag very rapidly during the excitement of CPR (generally in <0.5 s and with power), suggests the need for better teaching of basic manual resuscitation skill [48].

Limiting the size of the ventilating bag to a pediatric volume could theoretically decrease the danger of delivering an exaggerated tidal volume during CPR. However, if oxygen is not available at the scene of an emergency and small tidal volumes are given during BLS ventilation with a pediatric self-inflatable bag and room air (21% oxygen), insufficient oxygenation and/or inadequate ventilation may result [66]. In a recent study, 40 patients were randomly allocated to room-air ventilation with either an adult (maximum volume, 1500 mL) or pediatric (maximum volume, 700 mL) self-inflatable bag for 5 minutes while apneic after induction of general anesthesia before intubation [66]. When using an adult (n = 20) versus pediatric (n = 20) self-inflatable bag, tidal volumes and tidal volumes per kilogram (mean ± standard error of the mean) were significantly larger (719 ± 22 mL/kg *vs* 455 ± 23 mL/kg and 10.5 ± 0.4 mL/kg *vs* 6.2 ± 0.4 mL/kg, respectively; $P < 0.0001$). Compared with an adult self-inflatable bag, BVM ventilation with room air using a pediatric self-inflatable bag resulted in significantly lower arterial partial pressure of oxygen values (73 ± 4 mm Hg *vs* 87 ± 4 mm Hg; $P < 0.01$) but comparable carbon dioxide elimination (40 ± 2 mm Hg *vs* 37 ± 1 mm Hg; not significant), indicating that smaller tidal volumes of about 6 mL/kg (approximately 500 mL) given with a pediatric self-inflatable bag and room air maintain adequate carbon dioxide elimination but not oxygenation during simulated BLS ventilation. This study confirms previous observations that if small (6 mL/kg) tidal volumes are being used during BLS ventilation, additional oxygen is necessary, and when additional oxygen during BLS is not available, only large tidal volumes of about 10 to 12 mL/kg can be used to maintain both sufficient oxygenation and carbon dioxide elimination [18]. Although both the ERC and the AHA recommend decreasing tidal volume during BLS ventilation to minimize stomach inflation, the availability of an oxygen source should always be emphasized [2,49]

Specialized airway devices in cardiopulmonary resuscitation

Specialized airway devices in CPR include the laryngeal mask airway (LMA; Laryngeal Mask Co., San Diego, CA), the esophageal tracheal airway (Combitube; Kendall-Sheridan Catheter Corp., Argyle, NY), the pharyngotracheal lumen airway (PTL), the cuffed oropharyngeal airway (COPA; Mallinckrodt, St. Louis, MO), emergency tracheostomy and cricothyroidotomy, and endotracheal intubation. Although many of these devices have been extensively or anecdotally tested in the field during cardiac arrest, only a few of them have been included in the new AHA advanced cardiac life support guidelines for ventilation.

Laryngeal mask airway

Although recently introduced, the LMA already has a solid track record of "saves" in the established difficult airway and in specific unpredictable situations of the American Society of Anesthesiologists' difficult airway algorithm, such as emergency cesarian sections, airway trauma, and the newborn infant. Once placed, the LMA may be left in place to provide ventilation and oxygenation or may be exchanged for a more definitive airway. Based on widespread anesthesiologist experience with this device, the LMA should be considered first among the alternative airways to be used during CPR. The main limitations of the LMA are that it offers little protection against passive pulmonary aspiration of gastric contents, and its cuff limits efficacy in positive pressure ventilation.

The incidence of regurgitation during insertion of the LMA is controversial, and the only experience available is in patients with a difficult airway who are not in cardiac arrest. A recent observation in this setting shows that the LMA can be associated with risk of aspiration through relaxation of the lower esophageal sphincter, distention of the hypopharyngeal muscles, and prevention of ejection of regurgitated food [67]. Experienced practitioners consider the LMA in selected difficult airway conditions only when laryngeal obstruction, tumor, tonsillar bleeding, epiglottitis, or laryngeal abscess are absent. Although most of the literature on the LMA is available from anesthesiologists, the evidence in favor of this airway in prehospital difficult airway management and cardiac arrest is rapidly accumulating.

In the United States, specially trained paramedic and/or registered nurse flight crews perform airway management in the field. Although there is controversy as to what constitutes appropriate field airway management in the patient in cardiac arrest, most paramedics would ventilate using the BVM technique or by placing an endotracheal tube [68]. A prospective comparison between LMA and endotracheal tube management by paramedic students showed that LMA placement was successful on the first attempt 94% of the time compared with 69% in the endotracheal tube group ($P < 0.01$) [69]. The insertion of the LMA was also statistically faster to detection of end-tidal CO_2. The same observation was confirmed when respiratory therapists or medical students manipulated the airway [70,71].

The usual peak airway pressure limitation of the LMA is about 15 to 20 cm H_2O. As demonstrated in patients under an anesthetic that included neuromuscular blockade and mechanical ventilation, positive pressure ventilation with peak inflation pressures ranging between 15 cm H_2O and 30 cm H_2O may result in a progressive decrease in tidal volume from 13% to 27% and an increase in gastric esophageal inflation from 2% to 35% [72]. In this situation, the risk of gastric insufflation is aggravated by the fact that cricoid pressure cannot be applied without further displacing the LMA [73]. A modification of the LMA, the LMA-ProSeal (Laryngeal Mask Co., San Diego, CA) has been recently designed with an extra cuff and a channel that can accommodate a small nasogastric tube [74]. Unique advantages of this modified airway are the potential limitation of regurgitation of gastric contents in the pharynx and subsequent pulmonary aspiration and the ability to provide positive pressure ventilation up to a peak airway pressure of 30 to 35 cm H_2O, which are both desirable when attempting to ventilate a cardiac arrest victim [75]. However, there are currently no available clinical reports of the use of this device during CPR.

Combitube

The Combitube, an evolutionary step in the design of the esophageal obturator airway, provides a complete seal of the upper airway and, therefore, can be used in patients with a high-risk of regurgitation and aspiration of gastric contents [76]. The main indication for the Combitube has been in the rapid establishment of an airway during CPR [77,78]. The Combitube is essentially a double lumen tube that is inserted blindly through the mouth and is more likely to pass into the esophagus (80% of the time) than into the trachea (20% of the time). Both lumens are color-coded: blue for the esophagus and clear for the trachea. A proximal latex esophageal balloon (inflated first after placement) is filled with 100 mL of air, and a distal plastic cuff is filled with 10 to 15 mL of air. These cuffs provide a good seal of the hypopharynx and stability in the trachea or esophagus. The esophageal lumen is closed distally and perforated at the hypopharyngeal level with several small openings. The trachea lumen is open distally. The Combitube has the same limitations as the LMA and, thus, may not be suitable in patients with hypopharyngeal pathology or preexisting esophageal pathology, such as a malignancy or esophageal varices [79].

The Combitube is available in standard adult and small adult sizes. The most common reason for failure to ventilate with this device is placement of the device too deeply, so that the perforated pharyngeal section has entirely entered the esophagus. Pulling the Combitube back 3 to 4 cm usually resolves the problem. To minimize this problem, use of the smaller version for patients less than 5 feet tall is recommended by the manufacturer. Although our experience with this device is limited in both difficult airway and CPR scenarios, that of others seems to suggest that the smaller version has a higher chance of success and a lower risk of damaging the hypopharynx and the esophagus [80].

The Combitube can be inserted safely in patients with cervical spine injuries, because flexion of the neck is not required. However, it is not well tolerated in patients with a persistent, strong gag reflex after resuscitation and should be exchanged with an alternative airway as soon as possible.

Pharyngotracheal lumen airway

The PTL is essentially an improvement on the design of the esophageal obturator airway and the esophageal gastric tube airway [81]. Both devices are double-lumen airways that are inserted blindly, preferably into the esophagus. The PTL has an oral balloon that provides a seal for the airway. An inflatable distal cuff prevents aspiration of gastric contents. Just like the Combitube, the attendant should evaluate carefully if the device is in the esophagus or the trachea and, based on this evaluation, ventilate through the appropriate lumen.

Cuffed oropharyngeal airway

Although limited information has been published about this device, use of the COPA is intuitively easy [82,83•]. Once in place, one of the main advantages the COPA is the presence of a large, inflatable cuff that can splint redundant soft tissue in the pharyngeal space. This specially designed device includes a standard 15-mm connector that facilitates positive pressure ventilation via a self-inflating bag. Several sizes are available.

Laryngeal mask airway, Combitube, pharyngotracheal lumen airway, and cuffed oropharyngeal airway in cardiopulmonary resuscitation: review of recent relevant literature

An *in vitro* and *in vivo* comparison of the LMA and Combitube with BVM ventilation is available. In a bench model simulating cardiac arrest in which the compliance was set at approximately half of normal and resistance was doubled to simulate cardiac arrest conditions, both the LMA and Combitube proved to be superior to a facemask in providing effective ventilation [84]. Several issues make this study remarkable: (1) emergency medical service (EMS) training for the LMA and Combitube was brief but very successful; (2) the achievement of appropriate ventilation with BVM ventilation was approximately the fastest, whereas the Combitube was the slowest; and (3) there was significantly greater gastric inflation with BVM ventilation than with the alternative devices (peak airway pressures, 27 ± 2 cm H_2O *vs* 17 ± 2 cm H_2O *vs* 21 ± 2 cm H_2O, respectively). Emergency medical technician objective assessment during the study clearly favored both Combitube and LMA over BVM. Although short-term retention of skills was present in both LMA and Combitube placement, poor performance with the Combitube was usually noted 6 months after the initial training.

Recently, the performance of the PTL, Combitube, and the LMA were compared in 470 cases of cardiorespiratory arrest [78]. No significant difference was found in objective measurement of ventilatory effectiveness, as measured by arterial blood gas analysis and spirometry, between the three devices. This was a true prospective, randomized study with the patient blinded to oral airway and BVM ventilation versus alternative airway. The crossover mechanism allowed EMS personnel to use BVM ventilation and to switch to an alternative airway if ventilation was unsatisfactory.

Several interesting points can be drawn from this study. Overall, there was no statistically significant difference between any of the airways used, although a slight increased trend in hospital discharges was found in the patients in whom the LMA was used. Furthermore, there was a significant increase in successful LMA insertion amongst EMS personnel trained in the operating room versus on mannequins. The incidence of aspiration was not statistically different for any of the devices, including BVM ventilation. Although the study was unable to demonstrate a statistically different outcome between different airways and BVM ventilation, it should be noted that in 91% of the cases the cause of arrest was cardiac, a situation in which ventilation is believed not to be fundamental to survival for the first few minutes after the arrest. Furthermore, the observation of adequacy of ventilation was performed by the EMS personnel and physicians who witnessed the arrest and not by the investigators.

The Combitube and LMA seem to have a good track record in trauma. In a randomized crossover design, 12 Navy SEALs participated in a 2-week advanced battlefield trauma course based on an instructional video and mannequin training [85]. In these highly specialized paramedical personnel, placement of an endotracheal tube averaged about 36.5 seconds versus 40 seconds for the Combitube. LMA insertion time was significantly shorter (22 s) in simulated active combat trauma during which the battlefield was covered with smoke. This scenario can be extrapolated to paramedical personnel involved with scenes in which the victim cannot be immediately extricated and/or the airway cannot be accessed for BVM ventilation or tracheal intubation. Such scenarios have been described in case reports [86].

A remarkable advantage of the LMA is its rapid learning curve. Several recent studies show that minimally experienced staff on a ward can successfully use the LMA during CPR [87–89]. Ventilation efficiency with the LMA was also compared with BVM in personnel with no previous resuscitation experience [90]. The results were striking. The effectiveness of ventilation with the LMA by inexperienced paramedics was superior to the ability of anesthetists to use a facemask. Rapid insertion time is another advantage of the LMA. A number of studies seem to demonstrate that skilled and unskilled personnel can achieve control of the airway more rapidly with LMA compared with endotracheal intubation and more effectively compared with BVM ventilation [91–94].

A relative advantage of the Combitube over the LMA in a trauma and cardiac arrest situation is the decreased incidence of gastric regurgitation and pulmonary aspiration. However, a recent meta-analysis showed a very low incidence of aspiration when the LMA was used in fasting patients scheduled for elective surgery. The relevance of these findings in nonfasted trauma patients is questionable [95].

Several studies have described the use of the Combitube in the prehospital setting [96–98]. The Combitube was evaluated as a backup airway in case of failed endotracheal intubation. In a study of 52 patients in a rural prehospital system, successful ventilation was achieved in 69% [99]. Although the percentage of success was limited, this study highlights the importance of alternative ventilatory devices in both rural and nonurban systems in which the response to cardiac arrest and the availability of highly skilled paramedical personnel trained in cardiopulmonary arrest is limited. The rate of successful attempts for the Combitube increases to 100% in an urban environment where trauma patients receive care [100].

Close attention has been paid to the use of the alternative airway during CPR in patients with suspected cervical spine injuries. The LMA has the theoretical advantage of achieving control of the airway without manipulations of the neck [101,102]. However, recent studies in cadavers have shown a potential for increased posterior dislocations of the cervical spine with LMA use [103]. The Combitube has the potential advantage of being placed into the esophagus with the neck in an absolutely neutral and immobilized position. This allows for rapid airway control without removing a stiff cervical spine immobilization collar that is already in place. A preliminary study in healthy, anesthetized patients showed a high rate of success in ventilating patients with a cervical spine immobilization collar when the collar was positioned after placement of the Combitube [104]. However, when Combitube intubation was attempted in American Society of Anesthesiologists physical status class I and II patients with a cervical collar already in place, the rate of success decreased to only 33%. The use of gentle laryngoscopy, although not recommended by the manufacturer, improved the rate of successful insertion to 75% [104].

Little information is available on the use of the COPA during CPR. When a group of anesthetists compared the COPA with BVM and LMA in a prospective, randomized study, adequate ventilation was found to be superior with the COPA when positive pressure ventilation was applied [105]. Furthermore, in a crossover study, the COPA was found to be effective as a rescue airway to allow ventilation when BVM ventilation was clearly ineffective. However, no information was available on the incidence of gastric insufflation [106].

Tracheostomy and cricothyroidotomy

When the airway is compromised by trauma or when massive oropharyngeal or hypopharyngeal pathology is present, emergency access to the airway can be obtained only through an emergency surgical airway (tracheostomy or cricothyroidotomy) or a percutaneous cricothyroidotomy. Emergency tracheostomy is usually performed via a vertical incision from the cricoid cartilage down, for approximately 1 cm, in the direction of the sternal notch. A #11 surgical blade is preferably used. A skilled, surgically trained operator can rapidly approach the trachea via this route and insert a small, cuffed endotracheal tube. Emergency cricothyrotomy is a valid alternative to the emergency tracheostomy for an operator who is not skilled or trained in the surgical approach to the airway. This technique requires identification of the cricothyroid membrane. The cricothyroid membrane (ligament) is directly under the skin and is composed primarily of yellow, elastic tissue [107]. It covers the cricothyroid space, which averages 9 mm in height and 3 cm in width. The membrane is located in the anterior neck between the thyroid cartilage superiorly and the cricoid cartilage inferiorly and consists of a central triangular portion (conus elasticus) and two lateral portions. It is often crossed horizontally in its upper third by the superior cricothyroid arteries.

Because the vocal cords are located a centimeter or more above the cricothyroid space, they are usually not injured, even during emergency cricothyrotomy. The anterior jugular vein runs vertically in the lateral aspect of the neck and is usually spared injury during the procedure. There is, however, considerable variation in both the arterial and venous vessel patterns. Although the arteries are always located deep to the pretracheal fascia and are easily avoided during a skin incision, veins may be found in both the pretracheal fascia and between the pretracheal and superficial cervical fascias. To minimize the possibility of bleeding, the cricothyroid membrane should be incised at its inferior third. This technique has the relative advantage of achieving access to the airway through a relatively avascular part of the neck, especially in lean individuals. However, the cricothyroid membrane is not always easy to appreciate in obese patients or in those with a short neck. Melker and Florete [107a] have described percutaneous cricothyroidotomy using the Seldinger technique [108].

The main advantage of this technique is the blunt dissection of the subcutaneous tissues all the way to the cricothyroid membrane. An airway catheter is then introduced over a dilator threaded over the guidewire. This technique allows the ultimate insertion of an airway that is considerably larger than the initial needle or catheter and often of sufficient internal diameter to allow ventilation with conventional ventilation devices, suctioning, and spontaneous ventilation.

Needle cricothyroidotomy is an alternative to the use of the more invasive cricothyroidotomy or tracheostomy, regardless of whether it is surgical or percutaneous. This can be achieved with a large-caliber angiocatheter, usually #12 or #14 gauge, or a specialized armored #12 gauge angiocatheter. Needle cricothyroidotomy always requires the use of a jet device to provide ventilation, and it is associated with a high incidence of complications, such as massive subcutaneous emphysema, barotrauma with pneumothorax or tension pneumothorax, and air trapping with severe hemodynamic instability. Experience with needle cricothyroidotomy in CPR is limited.

Alternative methods to ventilation after successful endotracheal intubation

The relation between intrathoracic pressure and airway pressure during CPR has been recently studied [109]. A sudden increase in venous return during airway obstruction or exaggerated Mueller maneuver is known to be associated with negative pressure pulmonary edema [110]. During the decompression phase of CPR, venous return is enhanced. A small inspiratory impedance valve has recently been introduced to occlude the airway selectively during the decompression phase of CPR without interfering with exhalation or active ventilation. The effect of this device on the increased venous return during resuscitation has been recently studied in animals and humans. A remarkable improvement in all of the physiologic parameters correlated with restoration of spontaneous circulation after defibrillation was demonstrated (end-tidal CO_2, systolic blood pressure, diastolic blood pressure), and the beneficial effect of this valve could be seen on both models of protected and unprotected ventilation [111,112].

Application of continuous positive airway pressure (CPAP) without active ventilation has been recently studied in CPR. In a pig model of cardiac arrest, CPAP titrated to achieve 75% of a baseline end-tidal volume was compared with intermittent positive pressure ventilation [113]. Although a significant difference in both airway pressure and diastolic blood pressure could be detected between the two techniques (27 ± 58 mm Hg in CPR *vs* 13 ± 11 mm Hg in CPR_{CPAP}), there was an improvement in arterial and mixed venous pH, O_2 saturation, and CO_2 in the CPR_{CPAP} animals. Cardiac output did not change significantly between the two methods. This technique has the potential advantage of simplifying CPR, decreasing pulmonary atelectasis, and improving both oxygenation and ventilation. However, it can also have a negative effect on diastolic blood pressure and, thus, on both coronary and cerebral blood flow. When the effect of positive end-expiratory pressure was combined with that of negative inspiratory pressure on the inspiratory threshold valve (CPAP level up to 10 cm H_2O), the increase in oxygenation was still appreciated with improved respiratory system compliance but without detrimental effect on the hemodynamics [114••].

Transport ventilators

Although the introduction of transport ventilators for prehospital and hospital care was typically aimed at providing mechanical ventilation in patients with an endotracheal tube in place, some of their features can be used to provide ventilation of the unprotected airway during and after CPR. These devices are typically compact, lightweight, time or flow cycled, durable, pneumatically or electronically powered, easy to operate, and low maintenance. An excellent review is available in the literature [115].

Theoretically, both time or flow cycle transport ventilators can replace BVM ventilation during CPR. However, one particular model, the Ohmeda HARV or pneuPAC 2-R (Ohmeda Emergency Care, Orchard Park, NY), is commercially available for either transport ventilation or assisted mask ventilation. HARV produces a rectangular flow waveform that is time triggered, flow or pressure limited, and time cycled. A single control sets one of seven rate/tidal volume combinations. Mechanically operated mask ventilation undoubtedly presents advantages during CPR, because it frees the resuscitator's hand that typically is involved in squeezing the bag. However, the use of this pressure-powered machine that operates from an external pneumatic source (wall pressured oxygen or portable oxygen tank) presents the hidden danger of providing exaggerated tidal volume and/or excessive flow rate with short inspiratory time. Nevertheless, such a device could be helpful as an addition to the CPR health provider airway armamentarium, granted that the provider has the skill and knowledge necessary to operate it safely.

Conclusions

A number of alternative ventilatory methods are now available to provide oxygenation and correct respiratory acidosis in patients with cardiac arrest. Evidence-based medicine principles have improved the efficacy and safety of these devices during CPR. Both the AHA and the ERC incorporated these new strategies into the current version of the resuscitation guidelines. Although the need for immediate ventilation in CPR has been recently challenged in view of safety concerns, the importance of management of the airway and ventilation in the overall chain of survival from cardiac arrest cannot be overemphasized.

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