Neonatal resuscitation 1: A model to measure inspired and expired tidal volumes and assess leak at the face mask

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Abstract

**Introduction:** Neonatal resuscitation is a common and important intervention and adequate ventilation is the key to success. In the delivery room, positive pressure ventilation is given with manual ventilation devices via facemasks. Mannequins are widely used to teach and practice this technique. During both simulated and real neonatal resuscitation, chest excursion is used to assess tidal volume delivery and leak from the mask is not measured. We describe a system which allows for measurement of mask leak and estimation of tidal volume delivery.

**Materials and Methods:** We used respiratory function monitors, a modified resuscitation mannequin and a computer to measure leak from the mask and assess tidal volume delivery in a model of neonatal resuscitation.

**Results:** We measured the volume of gas passing through a flow sensor at the face mask. This was a good estimate of the tidal volume entering and leaving the lung in this model. We measured gas leak between the mask and mannequin. This occurred principally during inflation, though gas leak during deflation was seen when the total leak was large. We also measured a volume of gas that distended the mask but did not enter the lung.

**Conclusion:** This system can be used to assess the effectiveness of positive pressure ventilation given via a face mask during simulated neonatal resuscitation. This system could be useful for teaching neonatal resuscitation and assessing ventilation through a face mask.
Introduction

Internationally agreed consensus statements on neonatal resuscitation advise that the key to success is adequate ventilation.\(^1\) \(^2\) It is recommended that breathing be assisted by giving positive pressure ventilation (PPV) with a manual ventilation device via a face mask.\(^1\) \(^2\) Observation of chest wall movement is recommended to assess the adequacy of ventilation (i.e. gas delivery to the lungs),\(^1\) \(^2\) though the precision and accuracy of this assessment is not known. The technique of “bag and mask” ventilation is generally taught and practised using mannequins. Teaching and assessment of these techniques using mannequins form an integral part of neonatal life support courses which are a mandatory part of physician, midwife and neonatal nurse training in many countries.\(^3\) \(^4\)

According to consensus statements, most newly born infants can be adequately ventilated with a bag and mask.\(^1\) \(^2\) However the evidence to support this statement is lacking, the few studies of infants in the delivery room reporting that tidal volumes adequate for gas exchange were rarely delivered via a mask.\(^5\) \(^6\) \(^7\) There are no reported studies investigating resuscitation of very preterm infants via a mask. One study has assessed face masks used for neonatal resuscitation.\(^8\) The participants in that study had little or no experience in resuscitating infants, manual ventilation devices were not used and leak was not measured.

Giving PPV to a mannequin via a face mask mimics practice in the delivery room in that “chest” excursion is used to assess the adequacy of ventilation and there is no indication of the extent of the leak between the mask and face. To assess the adequacy of ventilation during resuscitation, measurement of the volume of gas entering and leaving the lungs (the tidal volume, \(V_T\)) would be ideal. This is, however, impractical unless the infant is intubated. In the absence of a direct measurement, an estimate of the tidal volume delivered during “bag and mask” ventilation, which was more accurate than the current “gold standard” of chest excursion, would be useful. A measure of leak occurring at the facemask would also be useful, as large leaks will reduce the tidal volumes delivered and thus the effectiveness of PPV.

We therefore modified a resuscitation mannequin so that we could measure the volume of gas passing through the mask and the tidal volume delivered to a test lung during simulated neonatal resuscitation. We wished to calculate the volume of gas leaking at the mask and determine how well the tidal volume returning through the mask represented the tidal volume returning from the lung.

Materials and Methods

Manual ventilation devices and face masks

The manual ventilation devices used at our hospital are the Neopuff Infant Resuscitator\(^\text{TM}\) (Fisher & Paykel Healthcare, Auckland, New Zealand) and the Laerdal Infant Resuscitator\(^\text{TM}\) (Laerdal Medical, Oakleigh, Australia). The Neopuff is a T-piece device that requires a compressed gas source. It has a valve on the outlet which allows for a positive end-expiratory pressure (PEEP) to be set for a given flow rate. Occlusion of this valve generates a predetermined peak inspiratory pressure (PIP). The Laerdal Infant Resuscitator is a 240 mL silicone self-inflating bag. We routinely
use round silicone Laerdal facemasks (Laerdal Medical, Oakleigh, Australia) with both devices at our hospital, and used the appropriate size mask (0/1) for the mannequin in this study.

**Modification of the mannequin**
The Laerdal Resusci Baby™ mannequin (Laerdal Medical, Oakleigh, Australia) is the most widely used resuscitation mannequin and has been found to be the most realistic for the purposes of simulated PPV. This mannequin is supplied with a bag in its “thorax”. When PPV is given appropriately, this bag inflates and slowly deflates, causing visible “chest” rise and fall. We replaced the bag with a test lung with a baseline volume of 50 mL (Dräger, Lubeck, Germany) and connected it via an airtight seal to the mannequin’s “oropharynx”, so that its’ inflation and deflation caused “chest” excursion similar to that of the original mannequin. A pressure monitoring line was connected immediately proximal to the test lung. The compliance of this model, calculated by measuring the inspired volume of the whole system when pressurised to 25 cm H₂O, was 0.46 mL/cm H₂O, comparable to that of an infant with respiratory distress syndrome.

**Respiratory monitor**
Two Florian Respiratory Monitors (Acutronic Medical Systems, Zug, Switzerland) were used to measure gas flow. This monitor uses a flow sensor with a hot-wire anemometer with minimal (<1 mL) dead space to detect gas flow. The monitor calculates the volumes of gas passing through the sensor by integration of the flow signal. The flow sensors from both monitors were placed in series and their volume measurement calibrated simultaneously using a fixed volume syringe. The monitors measure airway pressures directly and were calibrated against a column of water. The output from the Florian monitors was acquired via an analog-digital converter using the Spectra software program (Grove Medical, London, UK). This is a computer program specifically designed for the acquisition and analysis of respiratory signals.

**Values measured**
We placed one flow sensor (FS1, Fig. 1) between the manual ventilation device and the face mask. With this sensor we measured the volume of gas passing from the device through the mask – the inspiratory tidal volume at the mask \([V_{TI(mask)}]\) – and the volume of gas returning from the mannequin through the mask – the expiratory tidal volume at the mask \([V_{TE(mask)}]\). We placed the second sensor (FS2, Fig. 1) in the mannequin’s “airway”, proximal to the test lung. With this sensor we measured the tidal volume \([V_T]\) entering and leaving the test lung.

**Values calculated**
If the volume of gas passing from the device through the mask exceeded that returning from the mannequin through the mask, there was a leak between the mask and the face. This was calculated as their difference expressed as a percentage of the inspiratory tidal volume at the mask \([\text{leak} \text{ (\%)} = \frac{(V_{TI(mask)} - V_{TE(mask)})}{V_{TI(mask)}} \times 100]\). If leak from the mask was detected, we wished to determine whether it occurred during inspiration or expiration.

We hypothesised that if the volume of gas passing from the device through the mask \([V_{TI(mask)}]\) did not equal the volume returning through the mask from the mannequin
[\text{V}_{\text{TE(mask)}}] or the tidal volume measured in the mannequin [\text{V}_{\text{T}}], there would be 3 reasons:

1. **Leak during inflation:** In the presence of a poor seal between the mask and face, some of the gas passing through FS1 would escape during inflation and not pass through FS2 at the lung. The volume leaking during inflation would thus contribute to \text{V}_{\text{TI(mask)}} but not \text{V}_{\text{T}} or \text{V}_{\text{TE(mask)}}.

2. **Leak during deflation:** In the presence of a poor seal between the mask and face, some of the gas leaving the lung through FS2 would escape around the mask during deflation and not pass through FS1, resulting in \text{V}_{\text{TE(mask)}} underestimating \text{V}_{\text{T}}.

3. **Distension of the mask:** The mask used is made of distensible silicone; thus we hypothesised that, in the presence of a reasonable seal between the mask and face, gas under pressure would distend the mask but not enter the lung (\text{V}_{\text{MASK}}). This would pass through FS1 during inflation and back through FS1 during deflation, thus contributing to \text{V}_{\text{TI(mask)}} and \text{V}_{\text{TE(mask)}} but not \text{V}_{\text{T}}. This volume was demonstrated by placing the mask flat on a bench-top and giving positive pressure inflations (Fig. 2).

To test this system we recorded 100 inflations, applied by a consultant neonatologist, with varying amount of leak at the facemask, with each manual ventilation device. Inflations with a PIP of 25 cmH\(_2\)O and PEEP 5 cm H\(_2\)O were given with the Neopuff. With the Laerdal bag a manometer was placed in the circuit and a PIP of 25 cm H\(_2\)O was targeted for inflations. Data were analysed using SPSS for Windows (SPSS Inc., Chicago IL, USA). Results are expressed as mean (standard deviation).

**Results**

The mannequin’s airway and lung were leak free, with a difference between the volume entering and leaving the lung of –0.2 (0.5)%. There were no significant differences in the \text{V}_{\text{TI(mask)}}, \text{V}_{\text{TE(mask)}} or \text{V}_{\text{T}} delivered with each manual ventilation device.

**Relationship of \text{V}_{\text{TE(mask)}} to \text{V}_{\text{T}}**

The volume returning from the mannequin through the mask [\text{V}_{\text{TE(mask)}}] was a good estimate of the volume leaving the lung [\text{V}_{\text{T}}] (see Fig 3). When there were large leaks (>51%), \text{V}_{\text{TE(mask)}} tended to underestimate \text{V}_{\text{T}} because some of the gas returning from the lung escaped around the mask during deflation (see ‘Leak’ below). With smaller leaks \text{V}_{\text{TE(mask)}} tended to overestimate \text{V}_{\text{T}} because a volume of gas distended the mask but did not enter the lung (see ‘\text{V}_{\text{MASK}}’ below). Overall, \text{V}_{\text{TE(mask)}} was 100.6 (24.8) % of the lung \text{V}_{\text{T}}.

**Leak**

If the volume of gas passing from the ventilation device through the mask was greater than that returning from the mannequin through the mask [ie. \text{V}_{\text{TI(mask)}} > \text{V}_{\text{TE(mask)}}], there was a leak between the mask and the face. When the volume returning from mannequin through the mask [\text{V}_{\text{TE(mask)}}] was greater than or equalled the volume leaving the lung (\text{V}_{\text{T}}), all of the leak occurred during inflation.
When the volume leaving the lung ($V_T$) was greater than the volume returning from mannequin through the mask [$V_{TE(mask)}$], a proportion of the leak occurred in deflation. Leaks during deflation were never seen without a leak during inflation and only seen when the total leak was greater than 51%. When there was a large leak the proportion occurring during inflation $[(V_{TI(mask)} - V_T)/( V_{TI(mask)} - V_{TE(mask)}) \times 100]$ was 89 (10) % and the proportion during deflation $[(V_T - V_{TE(mask)})/( V_{TI(mask)} - V_{TE(mask)}) \times 100]$ was 11 (10) %.

**Volume distending the mask and not entering the lung ($V_{MASK}$)**

When the volume passing from the device through the mask [$V_{TI(mask)}$] equaled the volume returning from the lung [$V_{TE(mask)}$], there was no leak from the mask. During these inflations, a volume of gas distending the mask but not entering the lung [$V_{MASK}$] was readily demonstrated, as the volume passing through the mask flow sensor FS1 was greater than that passing through FS2 and entering the lung. While this became progressively smaller as the total leak increased, a volume of gas distending the mask but not entering the lung [$V_{MASK}$] was seen with leaks up to 51%. This volume [$V_{MASK}$] was 2.4 (1.4) mL, which represented 18.3 (10.5) % of the tidal volume delivered to the lung ($V_T$).

**Discussion**

Positive pressure ventilation using manual ventilation devices via a face mask is an important skill. It is widely taught and practised using mannequins. We have developed a system which allows for estimation of tidal volume delivered and measurement of mask leak during simulated PPV. The pressures used may also be recorded using this system. This system was developed with a view to recording real resuscitations in the delivery room.

Studies of PPV via a mask during resuscitation in the delivery room are few. In a study of term infants, “bag and mask” ventilation seemed relatively inefficient, with tidal exchange substantially less than that seen after intubation and rarely sufficient to produce adequate alveolar ventilation.\(^5\) It is worth noting that the apparatus used to measure expired tidal volumes in this\(^5\) and other assessments of “bag and mask” ventilation\(^6,\,7\) was similar to ours, in that the flow sensor (pneumotachograph) was placed between the manual ventilation device and mask. While the mask used for these studies differed from ours and its’ properties are likely not identical, there was leak from this mask during inflation. It is reasonable, thus, to speculate that there may also have been leak during expiration. It is unclear how the expired tidal volume reported [equivalent to our $V_{TE(mask)}$] related to the expired tidal volume leaving the lungs.

It remains unclear how effective “bag and mask ventilation” in the delivery room is as a means of delivering a satisfactory tidal volume, particularly in preterm infants of whom there are no reported studies. Moreover, this technique is not without its complications; bradycardia caused by application of a mask during neonatal resuscitation has been reported.\(^11,\,12\) Detailed studies of the efficacy of PPV via a face mask in newborn infants are needed, particularly in preterm infants. Applying a flow sensor between the manual ventilation device and face mask in the delivery room may give valuable insights into the effect of PPV on newborn infants during resuscitation.
Conclusions

We have developed a system for practising and assessing PPV via a face mask. In this model, the volume of gas returning through the face mask from the mannequin \( V_{TE(mask)} \) is a good estimate of the tidal volume entering and leaving the lung. The majority of leak from face masks occurs during inflation, though a small proportion does occur during deflation when the total leak is large (>51%). With leaks of up to 51%, a volume of gas distends the mask but does not enter the lungs. This data is useful to further evaluate resuscitation equipment and techniques in bench-top studies and in the delivery room.

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Competing interests

None

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Figure legends

**Figure 1**
Diagram of apparatus used to assess accuracy of measurements made with flow sensor 1 (FS1) using flow sensor 2 (FS2). \( V_{TI(mask)} \) = inspiratory tidal volume at the mask, \( V_{TE(mask)} \) = expiratory tidal volume at the mask, \( V_T \) = tidal volume

**Figure 2**
Trace obtained when the facemask was applied firmly to a flat bench-top so that no gas escaped, and positive pressure inflation was applied. This illustrates a volume of gas distending the mask that appears to contribute to tidal volume, but never enters the lung.

**Figure 3**
Scatterplot showing the relationship of the expired tidal volume at the mask \( V_{TE(mask)} \) to the tidal volume at the lung \( V_T \).
References


Volume at mask FS1 (mL)

Volume at lung FS2 (mL)
inflation deflation