Review of Optimal Characteristics of Face-Masks for Valved-Holding Chambers (VHCs)

Israel Amirav, MD1* and Michael T. Newhouse, MD, MSc, FRCP(C), FACP, FCCP2

Summary. Inhaled drugs are frequently given to infants and young children with a pressurized metered-dose inhaler (pMDI) attached to a valved-holding chamber (VHC) with face mask. In young children and infants who cannot breathe through a mouthpiece, the face mask serves as the interface between the patient and the VHC. Although the mask interface is one of the most important factors determining the dose of medication delivered from the VHC to the nose and mouth in these patients, its optimal characteristics are not well known. Recent studies clearly identify several face mask factors that determine the success or failure of drug delivery with these devices. This review summarizes the most important features of an optimal mask design such as: face seal/leak, volume of dead space, contour, flexibility, transparency, weight and cost. By optimizing these characteristics it should be possible to improve mask design. This will maximize the magnitude and reduce the variability of the dose presented to the respiratory tract while making the mask more comfortable and patient/caregiver-friendly.

Key words: aerosol; facemask; seal; metered-dose inhalers; children; dead space.

INTRODUCTION

Face masks are used for many respiratory care applications such as anesthesia, resuscitation, and aerosol therapy. In pediatric practice, particularly in infants and toddlers, aerosol therapy is usually administered by means of small volume nebulizers from which aerosol is delivered into the face mask. Due to their convenience, speed of administration and versatility, pressurized metered-dose inhalers (pMDIs) have become an increasingly popular alternative for providing therapeutic aerosols in children.1 To overcome coordination difficulties in young children pMDIs are commonly used with valved-holding chambers (VHCs). Initially, these chambers were simple tubes or containers (e.g., coffee cups, toilet rolls, modified 1–1.5 L plastic flasks), which were appropriately named spacers and had no valves. The main benefit of spacers, is to extend the distance between the actuator and the mouth thus allowing the larger aerosol particles that have little or no therapeutic benefit to decelerate and deposit in the spacer thus reducing ballistic and inertial impaction of particles in the URT. The spacer may, depending on its volume and configuration, allow larger droplets to evaporate before reaching the humid environment of the oropharynx, thus increasing the dose of LRT-targetable medication. This results in a decrease in systemic absorption and adverse effects. The main rationale behind the development of spacers was to provide a reservoir of aerosol, from which the patient could breathe, thus removing the need to coordinate the actuation of the inhaler with inspiration. While spacers still require hand-breath coordination, the development of relatively simple and practical spacers with valves, valved-holding chambers (VHCs) almost completely overcame this problem. In infants and young children up to about age 4 years who cannot reliably breathe through a mouthpiece, the face mask serves as the interface between the patient and the VHC. Face masks attached to VHCs have greatly advanced our ability to adequately treat the youngest infants.

Although the mask interface is one of the most important factors determining the dose of medication delivered from the VHC (or any aerosol source) to the nose/mouth of the infant or toddler, its optimal characteristics are not well understood and studies comparing...
various face masks are lacking. Most of the previous studies dealing with VHC performance have paid little attention to the face mask component. For example, in previous studies of VHCs with masks,\textsuperscript{2,3} parents were instructed to hold the mask tightly against the infant’s face and this was monitored and repeatedly reinforced during the study, thus eliminating any possible leak. However, in daily home use and without repeated emphasis on achieving a mask-face seal, some mask designs appeared to be inherently leakier than others.\textsuperscript{4–6}

The most important features of VHC mask design recently appreciated are: face seal/leak, volume of the dead space, and flexibility. Other factors such as transparency, weight and cost may also be important. Although there is inevitably considerable overlap and numerous interactions among these factors, we will discuss them separately recognizing that a change in any one of them may impact others. For better clarity, pictures of the masks discussed are enclosed in Figures 1–8.

**LEAK**

A good seal around the nose and mouth will ensure that inspiration takes place from the VHC and not from the environment.

Several recent studies emphasized the importance of a tight seal between the face and the mask rim and suggested that there is a great variability among face masks with respect to their ability to create a good seal and prevent leakage. It was less than a decade ago that it was occasionally reported that the mask could be an obstacle to adequate aerosol delivery.\textsuperscript{4,7} Zak et al.\textsuperscript{6} measured mask pressures in some 200 children who were breathing through VHCs and masks and found them to be highly variable and much lower than those measured when “breathing” was accomplished with a simulated breathing-programmed mechanical respirator, suggesting frequent air leaks around the mask in these children. A study published in Pediatrics in 2001\textsuperscript{5} emphasized that an effective mask seal is crucial for adequate therapy with VHCs. In that study the amount of leakage that occurred with three commonly used VHC masks was compared to that with the Hans-Rudolph anesthesia mask (Kansas City, MO). The Babyhaler (Glaxo GmbH, Germany), Aerochamber (TMI, London, ON, Canada) and Nebuchamber (AstraZeneca, Lund, Sweden) masks were evaluated. Of these, the Nebuchamber performed most...
poorly. Ventilation measured through this mask, when applied to the face of young children under simulated real-life conditions, was significantly reduced compared to the other three indicating a greater leak. The AeroChamber mask performed best and was similar to the Hans-Rudolph mask, considered the “gold standard.” Furthermore, the coefficient of variation of ventilation was greatest with the Nebuchamber mask, although ventilation through the other masks was also quite variable amounting to 25% even with the best performing (AeroChamber) mask.

Facemask seal has since received increasing attention. In an attempt to improve its performance, the poorly fitting ovoid mask supplied with the Nebuchamber VHC was replaced, by the investigators, with a better fitting round mask that increased the delivery efficiency of therapeutic aerosols in young children by 30%. This new Nebuchamber mask was subsequently used successfully in a study of infants and young children with acute asthma presenting to an emergency department. A similar attempt to improve the face mask fit was reported by Esposito-Festen et al. who attached a different round facemask to the Nebuchamber and evaluated drug delivery using a model of a 9-month-old infant. The authors showed that even with a round mask, the smallest mask leak significantly reduces the lung dose.

Using a single VHC and three different facemasks, Hayden et al. measured the inhaled mass (trapped on filters interposed between the spacer and facemasks) of budesonide in 24 young children (mean age 38 months, range 6–81 months). They found significant variability in drug delivery ranging from 0 to 120 mcg of the 200 mcg nominal budesonide dose. The authors stressed the importance of face mask seal although it was not addressed specifically in this study.

In a more recent study specifically designed to evaluate the effects of mask seal Smaldone et al. confirmed its critical role as the most important factor in the chain from the aerosol generator to the patient. Their data demonstrated that the lack of facemask seal negated most of the effects of detergent coating, which by reducing static charge in VHCs was assumed previously to be the major determinant of aerosol delivery from VHCs.
That the face-mask fit is important in day-to-day clinical practice, has been demonstrated by Janssens et al.\(^4\) who also showed increased variability with the poorly fitting mask supplied with the Nebuchamber VHC.

The topic of mask face seal was recently also discussed in a special symposium.\(^{14–16}\) The effect of crying on the mask to face seal is complex. It is suggested that infants’ resistance to the mask, caused by fear of being smothered, accounts for their crying and squirming. This in turn results in a vicious cycle potentiated by excessive force applied by increasingly frustrated caregivers in order to achieve a tight fit between the mask and the face of the child. Indeed, it has previously been shown that the commonest cause of a poor seal is crying and/or distress and how common is crying? Ritson et al.\(^{18}\) suggested that the child has become acclimatized, to maintain a good sealpush the mask away, thus making it difficult, at least until the child has become acclimatized, to maintain a good seal against the gel has not been studied. Similarly, Marguet demonstrated that crying occurs in a significant proportion (38%) of her young patients receiving inhaled therapy administered while they are awake.\(^7\)

To avoid crying, attempts have been made to administer aerosol drugs during sleep. Janssens et al.\(^{19}\) recorded the breathing patterns of awake and sleeping babies, ran them on a breathing simulator and showed that treatment during sleep greatly improved VHC aerosol delivery and doubled the “lung” dose compared to the awake state.

In an earlier in vivo study, Murakami et al.\(^{20}\) demonstrated in seven sleepy infants that scintigraphic deposition of nebulized aerosol appeared significantly better compared to when they were awake. The mean deposition during sleep appeared as good as that in co-operative older (3–14 years) awake children. However, sleep was induced, and it was thus not a “real life” study.

These promising results were somewhat contradicted during attempts to translate these in vitro improvements to real life situations. Noble et al.\(^{21}\) showed that although mask VHC aerosol administration during sleep was successful in most of the infants and toddlers, a subgroup of 17% of the patients awakened during the procedure. In a more recent study which directly assessed the effects of sleep on aerosol delivery by VHC, it was found that 70% of infants woke up during application of the mask and most of them (75%) became distressed.

The delivered dose in this case was almost half of the awake state.\(^{22}\) So aerosol administration during sleep is better-providing that you do not awaken the baby!

A good fit for a mask may be obtained using a very flexible, deeply rolled, edge. Air cushion at the leading edge is a possible alternative. The BreatheRite (Ventlab, Mocksville, NC) is an example of such a mask for VHC. This feature is commonly seen with many anesthetic masks. However, their applicability to VHCs is questionable because in order to conform to facial contours, the air cushion must be constructed of very thin plastic which is inherently fragile and may tear with repeated use.

Another recent development is a hydrogel applied along the leading edge of the mask. This has been used on face masks in adults receiving nasal continuous positive pressure ventilation. The gels seal well and readily adjusts to facial contours. The potential risk of skin irritation in children who may need to have frequent, although relatively brief, contact with the gel has not been studied.

The fit of the mask will also depend on the pressure applied by the caregiver and the cooperation of the child. Young children commonly resist a face mask at first. They often squirm and cry during initial treatment attempts and push the mask away, thus making it difficult, at least until the child has become acclimatized, to maintain a good seal with any existing mask.

**DEAD SPACE**

Any drug contained in the volume of air common to the inspiratory and expiratory pathways will be lost on expiration and not contribute to the lung dose. The smaller the mask and/or valve system dead space volume the more likely it is that a greater proportion of the dose in the VHC will be inhaled with each breath,\(^{23}\) thus speeding VHC emptying and improving overall aerosol delivery efficiency and dose. This is particularly important in neonates and infants under 1 year as well as toddlers or children with low tidal volume (\(V_t\)) and/or a high respiratory rate due to cardiopulmonary disease or metabolic acidosis. The \(V_t\) ranges from 10 to 20 ml in neonates at 30–40 breaths/min to 25–100 ml at 15–20 breaths/min from full term to age 18 months.\(^{24}\) Thus, in practice, with the Babyhaler’s, 77 ml mask dead space to which must be added a fixed 40 ml valve chamber dead space for a total of 117 ml dead space, only minimal amounts of drug would be delivered to the nose or mouth of infants younger than 1 year of age. With older infants, the mask dead-space decreases as the infant’s face grows and fills the mask.
while their tidal volume increases. Thus aerosol delivery becomes progressively more efficient with age.\(^{23}\)

A distinction should be made between the physical dead space of the mask and its physiological or functional dead space. By this, we mean that when a mask is applied to the face, the variable pressure applied causes compression of the mask and a variable reduction in the mask dead space. The difference between the two depends on the size and shape of the infant’s face which protrudes into the potential dead space of the mask. Thus, the most important factors will be the pressure applied by the caregiver, usually the parent, and the flexibility and/or compressibility of the mask. A recent paper by Shah et al.\(^{25}\) specifically address the issue of mask dead space and the effect of applying various forces on the dead space of masks applied to the face of a child surrogate. The authors tested seven commonly used face masks and measured their dead space volume (DSV) both under static conditions (no pressure applied) and with various applied forces. Mask DSV was measured using the face of a 2-year-old mannequin to which was applied masses of 1.5, 3.5, and 7 pounds. This approximates the range of forces applied by care givers when administering aerosols to infants and young children, a very elegant method of systematically simulating a real world scenario which had not been previously addressed.

Shah found variable values for DSV and changes in DSV with different masks. Intuitively, the greater the applied force the greater the reduction in the DSV. However, due mainly to the use of different materials with varying flexibility, not all masks behaved similarly under these conditions. Not surprisingly, the authors found that more rigid masks showed a smaller reduction in dead space in response to the forces applied and one of the tested masks was so rigid that no seal could be achieved, even at the maximum force applied.

Integration of the outlet valve within the mask further minimizes dead space-related drug losses and improves lung delivery.

CONTOUR

The contour refers to the shape of the leading edge of the mask that is in direct contact with the child’s face. This edge can be described in the coronal and in the sagittal plane. In general, masks have circular or ellipsoid contours in the coronal view. The non-circular contours are mostly triangular with the apex at the top covering the bridge of the nose. Very few masks have been designed with an anatomical contour which also has a sagittally contoured leading edge as seen with the Hans Rudolph anesthesia mask.

Use of an anatomical contour may aid parents in the correct placement of the mask. If the contour is not clearly defined and parents are not carefully instructed, they may become confused and apply the mask incorrectly. This was observed with the Nebuchamber as reported recently.\(^{4}\) Rounded circular coronal edges are easy to apply and minimize the risk of poor placement. On the other hand round masks may predispose to poor alignment and cause the MDI to be inserted off the vertical which may reduce drug output.

As previously mentioned we and others\(^{8,10}\) have replaced the anatomical mask of the Nebuchamber with a round one and demonstrated improved aerosol delivery by round masks. Surprisingly, both in our study and that of Esposito et al. the dose variability was not improved with the improved mask, but instead increased with decreasing cooperation. This leads us to suggest that while the mask configuration is indeed extremely important for determining the aerosol dose delivered, it is probably less important than the magnitude of the daily variation, which probably depends mainly on patients’ caregiver’s adherence to optimal mask fit and infants’ cooperation.

FLEXIBILITY

As small awake children are usually in constant motion there may be a much greater chance of a good fit when the mask material is flexible and allows some freedom of movement with minimal loss of contact and seal. Flexibility may also be important for minimizing the dead space if masks are more concave. Stiff masks will resist compression by the infant’s face so that the reduction in the dead space will be potentially much less than with flexible masks. On the other hand, excessive flexibility may result in mask prolapse as pressure is applied, making the design of the shank of the mask or the supporting collar very important. As reported by Shah et al.\(^{25}\) there is considerable variability related to their flexibility. Flexibility is determined by many factors among the most important of which are the characteristics and thickness of the silicone plastic used for the body and shank of the mask which may not be identical, and mask dimensions. The thinner the walls, the greater the flexibility. However, if the mask wall material is too thin the body of the mask may collapse and become distorted, thus breaking the face-mask seal or allowing the in-mask exhalation valve to leak when pressure is applied. Repeated excessive flexing may also shorten mask durability. When evaluating face mask for flexibility it may also be important to use also a pliable material to simulate skin and subcutaneous tissue rather than a rigid mannequin.\(^{26,27}\)

TRANSPARENCY

A transparent mask is intuitively advantageous when delivering aerosol medications by mouth or nose to babies. This has been the experience with feeding bottles and in the development of transparent VHCs. In this regard, the
opaque mask and steel body of the Nebuchamber or Vortex VHCs may constitute a disadvantage. Transparent VHC face masks and the bodies of the VHCs allow caregivers to see the cloud of aerosol entering the device and to view valve movement as an indication of aerosol delivery to the tidally breathing child. The AeroChamber Max incorporates an inspiratory indicator flap on top of the chamber that indicates to the caregiver that face mask seal is adequate for inspiratory valve opening and thus for drug delivery to the child. Perhaps even more important is the ability to see the infant’s nose and mouth as this appears to provide reassurance for the parents that the child is not being smothered. Transparent surfaces may however become obscured with time due to accumulation of drug powder or aging of the poor-quality plastic that is used in some of the cheaper devices. VHCs and masks can easily be cleaned by means of lukewarm (not hot) dishwashing detergent solutions (1 part in about 100 parts water). The VHC and mask should drip-dry overnight and not be rinsed or wiped dry. This minimizes the electro-static charge and optimizes VHC efficiency in VHCs not constructed of conductive materials.13 Newer VHCs are being made with static dissipative materials to enhance the dose to the patient.

WEIGHT, LENGTH, BALANCE

Intuitively, the lighter the mask (see Table 1), the easier it is for infants and/or caregivers to handle and hold. However, the weight of the mask itself may be less important than the weight, length and overall device “balance” of the VHC body. Looking at the VHC as a whole it can be appreciated from the table that whereas the Aerochamber mask alone is 3 times heavier than the Nebuchamber mask, the combined Aerochamber VHC + mask that is used in practice is shorter and lighter. The device length and weight may be problematic with the long Babyhaler and could become clinically relevant when children are holding the VHC with mask themselves as they get older and become more comfortable with the device or if caregivers are trying to keep the mask sealed around the nose and mouth of a squirming infant. It must be acknowledged that these issues are not supported by evidence and may be of relatively little importance if aerosol therapy is administered to young children during sleep.23

AEROSOL DELIVERY THROUGH MASKS: NASAL, ORAL OR BOTH?

The nose is designed to filter much of the particle mass from the inhaled air and the lung dose in adults and children may be reduced by 50% or more when inhalation is via the nose.28

A face mask with an internal septum that separates the nose from the mouth within the face mask, to prevent nasal breathing has been suggested.29 The value of this approach in most infants and young children up to about 18 months of age is questionable as most of the time they breathe preferentially through the nose and are more likely to become upset if this is not possible. The surface area of the nasal opening in infants is considerably larger (relative to the rest of the airways) than in older children and adults, thus the aerodynamic filtration efficiency of the nasal passages (which has never been studied) may be less important in this age group.

COST

Anatomically contoured masks are possibly somewhat more costly to manufacture because the mold is more complex and requires a higher degree of precision. The more complicated the mask design, the more material required, the type and quality (durability-related) and the presences of valves are likely to increase the cost of a mask. However, if a more complex mask design leads to improved acceptance and compliance by young children, improved disease control may actually reduce total healthcare costs.

ACCEPTANCE

As with many medical devices designed for infants and children special considerations need to be addressed regarding acceptance of the mask by the patient. It will be useful to include positive reinforcement for the child to make treatments more tolerable. Examples are the Funhaler device from Australia, a positive feedback of adequate breathing such as the Flow-Vu* Inspiratory Flow Indicator in the AeroChamber, and as previously mentioned comfortable rolled edges.

SUMMARY

In summary, with many VHC designs it appears that relatively little attention has been paid to the mask in contrast to the body and valves, whistles and MDI interface. More emphasis should be placed on mask design which is the first and arguably, the single most important component of the VHC system. In our view, the design of face masks for effective aerosol therapy in infants should incorporate, as a minimum, the following features: minimal dead space; a generous, soft inwardly

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Nebuchamber</th>
<th>Aerochamber</th>
<th>Babyhaler</th>
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<tbody>
<tr>
<td>Mask alone</td>
<td>12.7</td>
<td>30.2</td>
<td>51.1</td>
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<tr>
<td>Mask and VHC</td>
<td>119.7</td>
<td>71.7</td>
<td>190.7</td>
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<tr>
<td>Length (cm)</td>
<td>17</td>
<td>15</td>
<td>30</td>
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rolled edge; appropriate flexibility, transparency and low cost. The VHC-mask combination should be “patient friendly” - relatively light, well balanced and as well-suited as possible for achieving optimal aerosol delivery efficiency.

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