Physiology of Oscillating Positive Expiratory Pressure (OPEP) devices: Expiratory flow bias and justification for vPEP® Device

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Introduction

This report is a comprehensive clinical review of pulmonary secretion management in the normal and diseased patient, with particular attention to maximizing the clinical benefits of oscillating positive expiratory pressure (OPEP) technologies. It is meant to be used in addition to device-specific manufacturers' instructions and recommendations for use and is not intended to replace conventional product training and education by appropriate personnel/tools. All medical devices should be used at the discretion of a qualified medical professional who understands the clinical indications and contraindications for use.

Normal anatomy and physiology

There exist many clinical conditions in which retention of secretions in the lungs and airway lead to pathologic pulmonary function. Mucus secretions are made naturally in the lungs as a mechanism to avoid dryness of the pulmonary mucosa. Additionally, immunoglobulin antibodies are found naturally in pulmonary secretions as a defense against microbes that may be inadvertently inhaled during normal breathing, thus providing protection from infection.[1] In the non-diseased state, these pulmonary secretions are continuously purged from the lungs through three primary mechanisms: mucociliary clearance, cephalad airflow bias, and coughing.

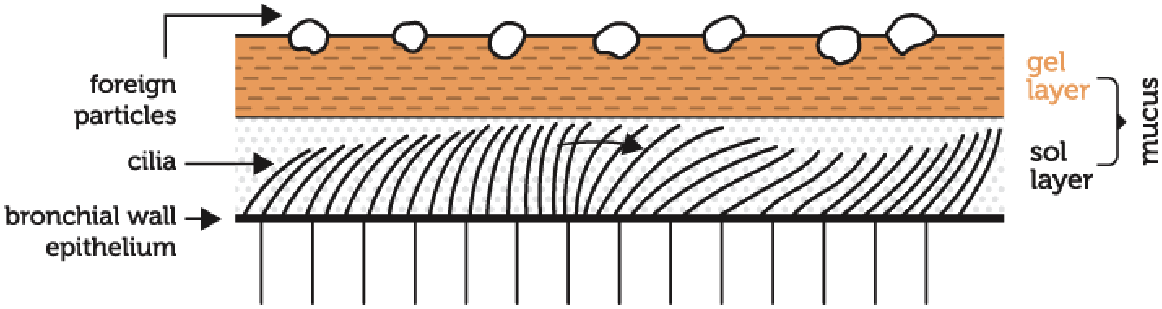

Figure 1: Graphical representation of mucociliary clearance. (http://bronchiectasis.com.au/physiotherapy/principles-of-airway-clearance/airway-clearance-in-the-normal-lung)

Mucociliary clearance

Cilia are microscopic hair-like projections that arise from the surface cells lining the respiratory tract *(Figure 1)*. These cilia beat in a coordinated wave-like motion at 11-13 cycles per second to carry secretions cephalad *(proximal; toward the larger airways; upward toward the oropharynx)* at a rate of approximately 4-5 mm/min. When secretions reach the larynx and pharynx, final clearance is achieved by swallowing.[2]

Cephalad airflow bias

Under normal physiologic conditions, the smaller, more distal airways are flexible and thus the diameter of these airways changes during inhalation and exhalation. Due to positive pressure surrounding the airway during exhalation, the inner diameter of said airways becomes more narrow. As the diameter decreases, the velocity of airflow concurrently increases, much the same way the velocity of water leaving a hose increases as you put part of your thumb over the exit *(Figure 2)*. The increased velocity of airflow creates a shearing force in the airway and an airflow bias directed cephalad towards the upper airways, moving secretions in that direction.[3]

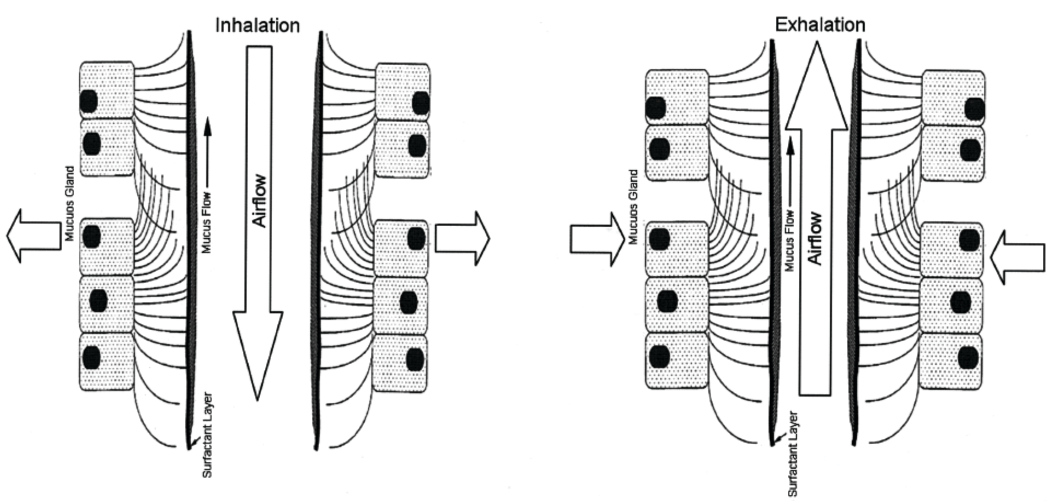

Figure 2: Cephalad airflow bias in the distal airways.[3]

Coughing

The mucociliary escalator and cephalad airflow bias are the primary mechanism of mucus clearance from peripheral and small airways, whereas cough is the primary method of clearing the larger, more proximal airways. The large positive pressures associated with coughing are ineffective to move mucus in the smaller airways, as they are flexible and collapse easily. However, the larger airways and trachea are thick-walled and contain cartilage that maintain patency despite high intra-thoracic pressures. Coughing creates high, turbulent airflow velocities in these airways with high shearing forces, propelling secretions upward and outward from the lungs.[3]

The directional movement of secretions is dependent on the combined principles of active mucociliary transport of mucus along with physical airflow principles that favor movement of secretions towards the oropharynx. These physical principles arise from natural or forced variations in airflow velocity during inhalation and exhalation. The volume of the inhaled and exhaled breath will always be equivalent *(you breathe out what you've breathed in)* but the time it takes for that breath *(and hence velocity)* may differ between the two.

Analogy:

Imagine standing in a wind tunnel where you experience a gentle breeze in one direction over the course of several minutes and then hurricane-like winds in the opposite direction for just a few seconds. Surely the gentle breeze won't force you to move very far despite several minutes, but the hurricane winds may blow you down the tunnel quite a distance in only a few seconds. The volume of air moved in both directions may be equal, but the velocity of wind determines which direction you are moved. The same is for secretions in the airway. If the velocity of air movement during exhalation exceeds that of the velocity during inhalation, secretions will naturally travel in that direction, towards the upper airway and out of the lungs. This principle is known as **Expiratory Flow Bias**, where a peak expiratory flow (PEF) rate exceeds peak inspiratory flow (PIF) rate, generating an overall flow bias towards the mouth during exhalation.

Key point:

In order to successfully move secretions toward the oropharynx, investigations demonstrate that the peak expiratory flow rate must exceed peak inspiratory flow rate by at least 17 liters per minute (LPM) or 10% (1.1*PIF).[4,5] This is the fundamental principle by which secretions are evacuated from the respiratory tract and *by maximizing expiratory flow bias, one can maximize the efficiency of airway clearance technologies* and improve patient care.

Pathophysiology

In pathologic conditions, any or all of the previously mentioned mechanisms for secretion clearance may be impaired. For example, in cystic fibrosis there is excessive mucus secretions, coupled with impaired mucociliary clearance leading to retention of secretions, mucus plugging, atelectasis, and chronic pulmonary infections. These chronic infections lead to structural damage, particularly of the smaller flexible airways, resulting in inefficient cephalad airflow bias and non-productive coughing. In COPD patients, collapse of the smaller airways during exhalation causes air and mucus trapping in the distal airways and secretion build-up.

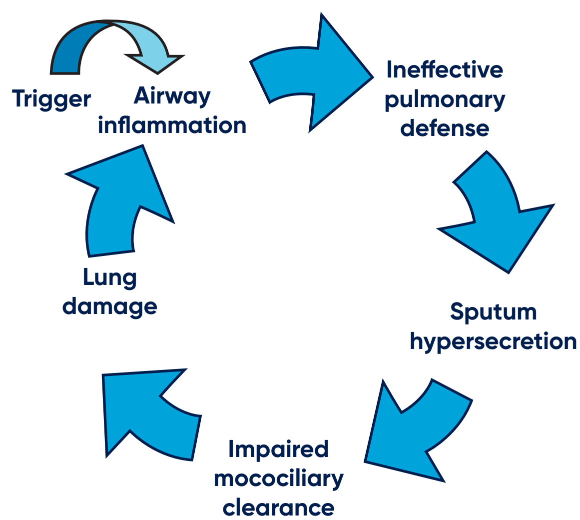

Figure 3: The Vicious Cycle Hypothesis.[7]

To sum up, in general the "vicious cycle hypothesis" explains how compromised secretion clearance resulting in inflammation and bacterial infection leads in a circle to further defects in secretion clearance and further progression of mucus retention and lung damage *(Figure 3)*.[6,7] Incorporating treatment methods within the cycle is critical to halting or reversing the progression of both acute and chronic lung conditions.

Treatment

When normal physiologic clearance of secretions is impaired, airway clearance treatment methods revolve around using productive breathing techniques *(e.g. huffing, coughing, autogenic drainage)* or secretion clearance devices/procedures *(e.g. chest physiotherapy, high-frequency chest wall compression, positive expiratory pressure, oscillatory positive expiratory pressure)*. The goal is to assist the body's natural mucus secretion clearance system and optimize expiratory flow bias to transport secretions proximally up the airways. Airway clearance techniques and devices are considered to be essential for optimizing respiratory status and reducing disease progression.

All breathing techniques *(huffing, autogenic drainage, etc.)* utilize the principles of cephalad airflow bias to naturally force secretions into the larger airways to be expelled via coughing. They are patient-dependent, requiring appropriate patient effort and participation; and are thus prone to failure when pathophysiologic disease states inhibit their effectiveness. For these patients, it is important to use adjunct devices to modulate or augment the normal physiologic abilities to maximize efficiency when the patient's disease or effort is insufficient.

Chest physiotherapy, percussion, and clapping

Chest physiotherapy is considered the Gold Standard of airway clearance techniques. The therapy involves manual percussion of the patient's chest by a caregiver with the goal of loosening or dislodging secretions from the walls of the respiratory tract, allowing for more productive cough efficiency. It is often performed with postural changes, specifically head-down posturing to utilize gravity to better promote cephalad movement of secretions in the airways. It is effective but carries several disadvantages. It is time-consuming for both the patient and caregiver, requires high-level patient cooperation, and is skill-based and labor intensive for the caregiver. For these reasons it is not always simple to perform appropriately on all patients and necessitates supplemental modalities for effective secretion clearance.

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High frequency chest wall oscillation (vest)

This therapy refers to a vest device that is worn by the patient. When connected to an air-pulse generator, the vest can inflate and deflate quickly with air *(5-20 times per second)*, creating a vibration-like environment within the lungs and intermittent increases in airflow. Much the same way Chest Physiotherapy works by loosening secretions for improved mobilization along with cough-like shear forces from airflow oscillation, this technique does so with less caregiver exertion and time, improving workflow. This device is seen most commonly used at home in pediatric patients with chronic pulmonary diseases caused by impaired secretion clearance, namely cystic fibrosis.

Positive Expiratory Pressure (PEP)

In the pathologic lung, the presence of excess secretions in the small airways, along with decreased structural integrity of the airway walls from chronic disease leads to easy collapse and mucus plugging in the distal airways. When the small airways collapse *(or obstruct from mucus)*, air is trapped behind the obstruction with no way of getting out. Over time, this leads to alveolar collapse *(atelectasis)* and retained secretions with increased risk of pulmonary infections. Secretions cannot be removed if there is no airflow in the diseased regions of the lung, therefore therapies exist in order to open these diseased airways and allow for airflow to occur. When the airway is patent and expiratory flow bias is achieved, improved oxygenation and outward movement of secretions is possible.

Positive airway pressure, achieved with many medical devices, can create a pneumatic stent whereby the collapsible airway segments remain patent. By stenting open the distal airways during exhalation using Positive Expiratory Pressure (PEP) and preventing the pathologic collapse, airflow during exhalation is possible to mobilize secretions. During PEP therapy, the patient exhales against a threshold resistor, generating positive pressure

Collateral ventilation plays a large role in PEP therapy as well. In the normal lung, there exist small channels between alveoli, bronchioles, and bronchi, allowing for communication *(Figure 4)*. During normal breathing, these channels remain closed due to very high resistance compared to normal pathways *(bronchi to bronchiole to alveoli)*. In the setting of mucus plugging in the normal pathways, the addition of positive airway pressure is sufficient to open these collateral channels and allow for ventilation "behind" mucus obstructions.[8] Positive pressure builds behind mucus plugs leading to ultimate release and expulsion, improving secretion drainage while also improving atelectasis and gas exchange in diseased segments of the lung.

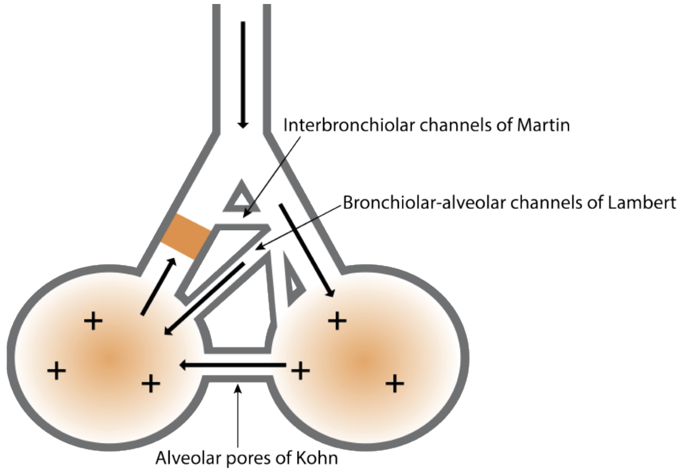


Figure 4: Collateral ventilation pathways. (http://bronchiectasis.com.au/physiotherapy/techniques/the-active-cycle-of-breathing-technique)

Pitfalls to PEP therapy:

As with all treatments in medicine, too much of a good thing is bad. There are limits to how much positive pressure should be applied to the airway before causing potential damage. Although there are no clear guidelines on the most effective expiratory pressure for secretion clearance, the recommended range is between 5 and 20 cmH_2O, whereas expiratory pressures greater than 20 cmH_2O are generally not recommended.[9,10] At pressures exceeding 20 cmH_2O, there is increased risk of barotrauma, pneumothorax, air-trapping, ventilation-perfusion mismatch, decreased cardiac output from reduced venous return to the heart, and increased intra-cranial pressure.[11–13] Additionally, high expiratory pressures may limit expiratory flow rate *(Poiseuille's Law)*, thus reducing the expiratory flow bias required to move secretions out of the airway.

All PEP and OPEP devices successfully generate positive pressure during exhalation capable of stenting open the airways and improving collateral ventilation behind trapped secretions. However, in simulation at high flow rates, some manufacturers' PEP devices have been shown to deliver pressures > 20 cmH_2O, which is a known risk of PEP devices. It is prudent to consult with a clinician and the Instructions for Use prior to using PEP therapy if a patient is at increased risk for these side effects.[9,14]

Oscillatory Positive Expiratory Pressure (OPEP)

As an adjunct to PEP therapy on its own, many devices improve secretion removal by incorporating high frequency oscillations to exhalation. The oscillations, through changes in resistance, induce vibrations within the airway wall to decrease the viscosity of secretions and displace them into the airway lumen.[5] Repeated airflow accelerations from oscillations function like a series of mini-coughs in the distal airways, rather than conventional coughs working on the larger airways, favoring movement of secretions into the more proximal airway for expulsion. For oscillations to be effective, both frequency and flow amplitude are important to consider.

1. Oscillation frequency

Oscillations have a productive effect on mucus rheological properties, decreasing rigidity and improving the cough clearance index.[5] To put it simply, it decreases viscosity, loosens up the mucus, and makes it easier to transport and expel. Effective frequency for this physical change is between 5-17 Hz which corresponds with physiologic frequency of ciliary beats.[5] Most OPEP devices oscillate within this range and there are no large differences between brands.[8,15]

2. Oscillation amplitude

Oscillation amplitude, however, differs greatly among manufacturers.[16,17] Knowing that flow velocity is critical to secretion movement, the amplitude, or change in flow velocity during exhalation, correlates well with efficacy. The greater the flow amplitude of oscillations, the greater the air turbulence caused within the smaller airways, creating an environment more capable of mobilization of secretions away from the airway walls.[18] Of course peak velocity is also important. Consider a change from 1 LPM to 25 LPM representing an oscillation amplitude of 24 LPM, and compare that to an oscillation from 15 LPM to 35 LPM with amplitude of 20 LPM. Although the amplitude in the first scenario is higher, the peak velocity *(and hence expiratory flow bias)* will be greater in the second scenario. The ideal device would have a large flow amplitude during oscillations with high peak velocity.

> *"Understanding all that we know currently about secretion mobilization and clearance, it is clear that the most efficacious device will maximize expiratory flow bias."*

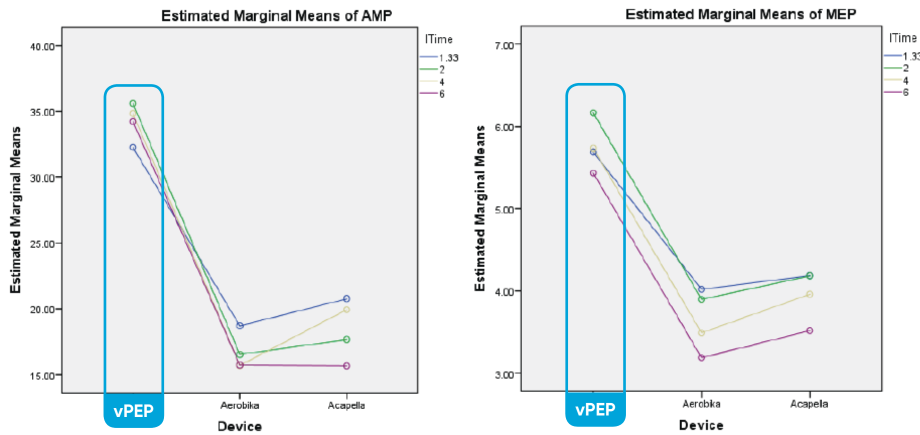


Figure 5: Oscillation flow amplitude and mean expiratory pressure across four inspiratory times for three OPEP devices.[17]

In comparing three leading OPEP devices, **Pursley demonstrated superiority of the D R Burton vPEP device** in both oscillation amplitude *(Figure 5)* along with peak expiratory velocity demonstrated with flow-volume loops across different resistances and tidal volumes *(Figure 6)*. The vPEP device did so with higher mean expiratory pressure as well, with the benefit of potential improved collateral ventilation and efficacy *(Figure 5)*.

Achieving maximal expiratory flow bias

Understanding all that we know currently about secretion mobilization and clearance, it is clear that the most efficacious device will maximize expiratory flow bias. This can be accomplished by two mechanisms, likely in tandem:

Decrease inspiratory flow rate

By taking slow deep breaths during inhalation, just like the gentle breeze in the wind tunnel analogy above, secretions are less likely to be driven deeper into the airways and lungs. Normal OPEP device techniques should revolve around purposefully slow inhalation followed by forceful exhalation, however, many manufacturers' instructions for use recommend inspiratory:expiratory time ratios of 1:3 or 1:4, in stark contradiction to this powerful principle.[17] The D R Burton vPEP device provides clear instructions to providers and patients that emphasize the use of very slow deep breaths during use. Despite receiving the same instructions for use, the mean inspiratory time of 42 healthy volunteers during OPEP therapy was 2.02 seconds with a range from 1.13 – 3.52 seconds.[19] This is important because variation in use will exist among patients using any device. In addition to clear instructions, the vPEP device provides slight inspiratory resistance, further promoting slow inhalation with decreased peak inspiratory flow, particularly in patients for whom following commands is more difficult. This decreases user variability and allows for maximal efficacy across different patient demographics and effort abilities.

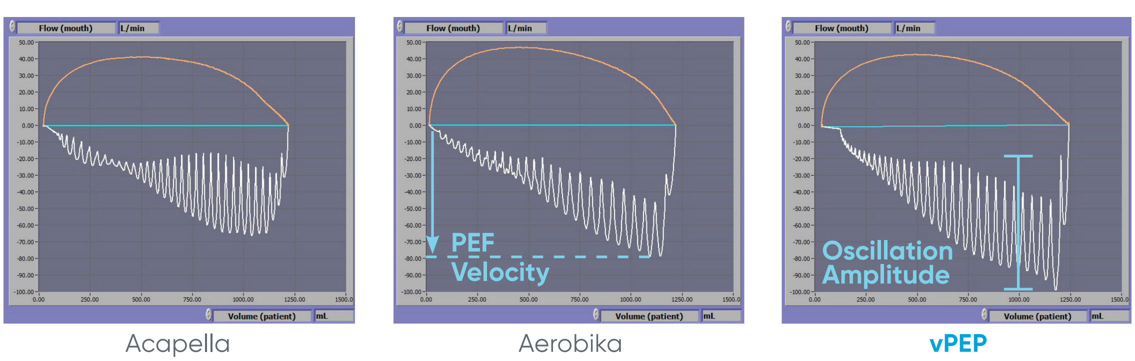
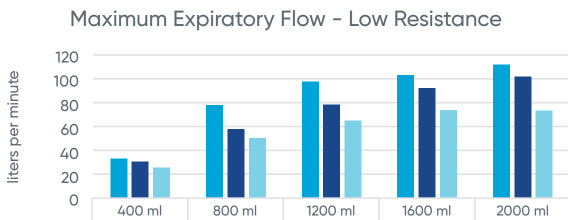
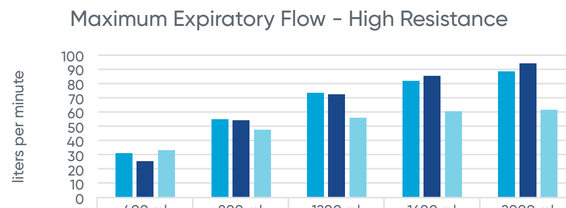


Figure 6: Flow-volume loops captured at a tidal volume of 1200 mL, inspiratory time 4 seconds, and active expiratory time of 4 seconds between three OPEP devices.[17]



	400 ml	800 ml	1200 ml	1600 ml	2000 ml
vPEP	32.6	77.9	97.1	103.4	112.7
Aerobika	30.5	57.3	78.9	91.6	101.4
Acapella	25	49.9	65.3	73.7	73



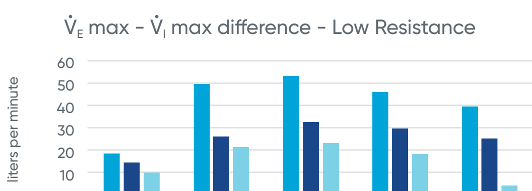
	400 ml	800 ml	1200 ml	1600 ml	2000 ml
vPEP	30	53.9	73.1	81.6	88.5
Aerobika	25.4	54	72.3	85.2	94.2
Acapella	33	48	55.9	60.2	61

Figure 7: Maximum expiratory flow at the lowest and highest resistance setting between three OPEP devices.[16]

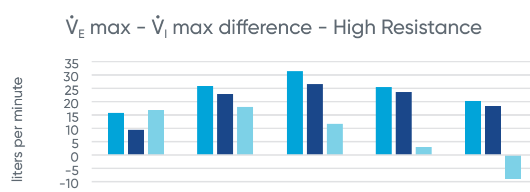
Increase expiratory flow rate

By maximizing expiratory flow rate, again you are able to manipulate the expiratory flow bias to improve efficacy. Along with slow deep inhalations, high-velocity exhalation promotes secretion clearance. **In a side by side comparison of three OPEP devices, D R Burton's vPEP device performed the best across a variety of tidal volumes and resistance settings, further promoting its efficacy and low variance across different settings and patient efforts *(Figure 7)*.**[16]

If inspiratory flow is lowest with the vPEP device, and expiratory flow is the greatest, it makes sense that the expiratory flow bias *(PEF-PIF)* should be greatest with this product as well. **In a simulated human lung model, the vPEP device showed a superior expiratory flow bias across five different tidal volumes and 2 different resistance settings *(Figure 8)*.**[16] **All except one measurement *(low tidal volume, high resistance)* fell below the previously recorded critical value for secretion movement *(17 LPM flow bias)*. The Acapella device performed poorly with 6 of 10 measurements falling below the 17 LPM critical expiratory flow bias, and one measurement *(high volume, high resistance)* favoring an *inspiratory* flow bias, with the potential to drive secretions *further* into the lungs.**



	400 ml	800 ml	1200 ml	1600 ml	2000 ml
vPEP	18.3	49.6	53.3	46.3	39.9
Aerobika	14.5	26.2	32.7	29.7	25.2
Acapella	10.3	21.5	23.3	18.3	4.4



	400 ml	800 ml	1200 ml	1600 ml	2000 ml
vPEP	15.6	25.7	31.4	24.7	19.7
Aerobika	9.5	22.8	26.4	23.2	18.2
Acapella	16.6	18	11.8	2.8	-9.2

Figure 8: Maximum expiratory minus maximum inspiratory flowrate difference at the lowest and highest resistance settings between three OPEP devices.[16]

Conclusion

The success and efficacy of Oscillating Positive Expiratory Pressure devices are a function of positive expiratory pressure, oscillation frequency, oscillating flow amplitude, and expiratory flow bias. The D R Burton vPEP device delivers superior oscillation amplitude, peak expiratory flow rate and expiratory flow bias compared to other OPEP devices. It is purposefully designed to improve secretion management in at-risk patients.

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