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Effects of Asymmetric Airway Inertance on Mean Lung Volume During High Frequency Ventilation(HFV)

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= Abstract =

A possible asymmetry in airway inertance was modeled based on previously reported radiographic visualization data of the airway wall fluctuation in intact dogs. Effects of asymmetric inertance on mean lung volume during high frequency ventilation (HFV) were evaluated in terms of mean inertive pressure drop across the airways. It was found that a negligible inertive pressure drop was expected (<1 cmH_2O) in normal subjects, while a significant rise in mean alveolar pressure compared to mean mouth pressure by approximately 3 cmH_2O was resulted for about 40% airway fluctuation representing bronchoconstriction state by Histamine induction. These results demonstrate that asymmetric inertance could lead patients with airway diseases to a significant lung hyperinflation (LHI), and bronchodilation treatment is recommended prior to applying HFV to prevent those patients from a possible barotrauma.

I. INTRODUCTION

It has been repeatedly reported that mean lung volume has been increased during high frequency ventilation (HFV)[1,2,3]. This phenomenon is called lung hyperinflation (LHI), which has been studied by many investigators, since it could limit the clinical advantages of HFV to a significant degree. Non-linear behaviour of the airways has been suggested to mediate LHI[4,5]. When airway mechanics is studied, the airways are usually assumed to be a rigid pipe having no dimensional change. However, Gavriely et al[7]. recently visualized the airway movement through radiography, and directly quantified the degree of airway diameter fluctuation. Since airway inertance should be related to this dimensional fluctuation(explained later), it would contribute to LHI if the fluctuation is asymmetric between inspiration and experation.Furthermore, Isabey and Chang[6] found that the pressure-flow loop of a human airway model could not be closed at the zero flow point by subtracting a term proportional to volume acceleration. This was especially true at wuch higher fregurencies, implying that the gas inertance was asymmetric (or, in general, non-linear). If the pressure-acceleration relationshp has an asym-

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metry in such a direction that lung volume could be increased during HFV, asymmetric gas inertance could be a cause of LHI. The present study modeled asymmetric inertance of the airways based on Gavriely et al, 's[7] direct visualization data of airway fluctuation tc evaluate the effects on mean lung volume (or LHI) during HFV. A possible range of the asymmetric inertance component of LHI was estimated to provide a guideline to minimize LHI in clinical HFV application.

Ⅱ. METHODS

(1) Gas inertance of a pipe line

Gas inertance (I_g) is defined as the ratio of inertive pressure component(P_I) to volume acceleration.

$$I_g=P_I/(d^2V/dt^2) \qquad (1)$$

where V and t represent volume and time, respectively. The force(F_I) required to accelerate gas having the density, ρ, in a tube with radius, r, and length l, along the longitudinal dimension, x, is

$$\begin{aligned} F_I &= m\,a \\ &\rho\pi\, r^2\, l(d^2x/dt^2) \end{aligned} \qquad (2)$$

where m and a are mass and acceleration, respectively. Since pressure is expressed as the ratio between force and cross－sectional area, $\pi r^{2,}$

$$\begin{aligned} P_I &= F_I/\pi r^2 \\ &=\rho l(d^2/dt^2) \end{aligned} \qquad (3)$$

Dimension, x, is converted into volume, V, as

$$dV=\pi r^2\, dx \qquad (4)$$

By substituting Eqs. (3) and (4) into Eq. (1),

$$I_g=\rho l/\pi r^2 \qquad (5)$$

Note, in Eq. (5), that gas inertance is inversely related to r^2 for a given gas filling a constant length tube. If the human airways can be modeled as a tube varying only its overall diameter, the inertance can be also assumed to vary with the diameter according to Eq.(5).

(2) Airway fluctuation and inertance asymmetry

As found in intact dogs by Gavriely et al[7], airway diameter fluctuates during HFV. When the diameter fluctuates from do－△d to do＋△d, where do is the diameter before HFV application and △d represents the amplitude of fluctuation, the maximum (I_D) and the minimum (I_I) inertances occur at peak deflation and inflation points, respectively, i. e.,

$$I_D=I_0[d_0/(d_I-\triangle d)]^2 \quad \text{at } d= d_0-\triangle d \qquad (6a)$$

$$I_I=I_0[d_0/(d_0+\triangle d)]^2 \quad \text{at } d= d_0+\triangle d \qquad {}_0(6b)$$

where l_0 is the inertance at midpoint or that without fluctuation (normal inertance). If inertances do not change, but maintain those values shown in Eqs. (6a) and (6b) during the deflation and the inflation periods, respectively, the maximum asymmetry is obtained resulting in the upperbound of inertive pressure difference between the deflation and inflation periods.

Since mean inertive pressure drop from alveoli to the morth (P_I), which contributes to LHI, is calculated by averaging the inertive pressure component as

$$\begin{aligned} p_I &= I_g(d^2V/d_t^2) \\ &< (I_D-I_I)(d^2V/dt^2) \\ &\;\; 2(I_D-I_I)f\int_0^{T/2}(d^2V/dt^2)dt \end{aligned} \qquad (7)$$

where f and T represent ventilation frequency and period, respectively, When the flow is a asymmetric sinusoid,

$$dV/dt=(\pi fV_T)\ \sin(2\pi ft) \qquad (8)$$

where V_T the tidal volume. Differentiating Eq.

(8). and integrating over a half cycle gives $4\pi f^2 V_T$, and this volume is substituted into Eq.(7). to obtain the upperbound of P_I as

$$p_I < (16\pi I_0)(f^2 f_T)[k/(1-k^2)^2] \quad (9a)$$

$$k = \triangle d/d_0 \quad 0 < k < 1 \quad (9b)$$

Eq.(9). was completed by substituting Eq.(6). for the expressions for I_D and I_I into Eq[7]. P_I in Eq(7). always results in a positve value since I_D should be larger than I_I in Eq(6). and Eq.(9). provides the upperbound of P_I. In other words, the present analysis only provides the possible range of P_I. However, the present analysis clearly demonstrates that the inertance asymmetry caused by the airway fluctuation could result in a positive mean pressure drop across the airways. Thus, during HFV application, mean alveolar pressure could be higher than the mean pressure at the mouth, which could force mean lung volume to rise, leading to LHI.

Ⅲ. RESULTS AND DISCUSSION

Since the upperbound of P_I given Eq.(9). is a monotonically increasing function of f, V_T, no optimal solution exists to minimize P_I(or LHI).

Table 1 The upper bounds of P_I for various degrees of airway fluctuation. $f=20$ Hz, $V_T=100$ml, and $I_0=0.0015$ $cmH_2O\ s^2/l$ were used

K	$P_I(cmH_2O)$
0.1	0.31
0.2	0.65
0.3	1.09
0.4	1.71
0.5	2.68
0.6	4.42
0.7	8.11
0.8	18.61

An arbitrary minimal value of $P_I=$ cmH_2O isw chosen in the present study which can be considered to have negligible effect on mean lung volume. Considering that the mormal lungs and thorax show a compliance value of 0.1 l/cmH_2O in adult humans, only 100ml increase in mean lung volume is expected. This value is equivalent to approximately 5% increase of normal functional residual capacity (FRC). Depending on the environments of HFV application, this value could be set lower.

When the ventilation frequency and tidal volume are 20 Hz and 100ml, respectively, P_I in Eq.(9). was calculated for different k values in Table 1. The normal inertance value of 0.0015 $cmH_2O{*}^2/l$ was used. Since k represents the degree of airway fluctuation, and the maximum k observed in diseased cases, by Gavrieoy et al. (71),was 0.8(80% fluctuation), k values used were limited up to 0.8 with decimal increasements. Table 1 shows that P_I becomes substantially higher than I cmH_2O for k values larger than 0.4, which is the minimum fluctuation level observed in Histamine induced bronchoconstriction[7]. Also, note that P_I dramatically increases with k above this level. This demonstrates that the airway fluctuation does not cause a significant rise in mean lung volume via inertance asymmetry in normal subjects, but patients with bronchoconstriction are vulnerable to airway fluctuation as far as mean voluve is concerned. Therefore, HFV has to be applied to those patients with other treatments reducing airway fluctuation such as broncho-dilator and/or positive pressure to increase the overal airway diameter, resultantly decreasing k-value.

One might argue that this may not be a serious problem, since the present analysis is limited to the upperbound of the possible LHI. However, the assumption made for the present analysis that inertance keeps the maximum and the minimum vlaues during the deflation and the inflation periods, respectively, have the following experimental evidences. According to Gavriely et al's[7]. direct observation, airway elongation was disproportionate to airway distention, implying that the airway diameter fluctuation is not related to the length change of the airways during HFV. Furthermore, the airways often showed a movement resembling a rectified sine wave during the deflation period, reflecting that the movement of airways does not have the same sinusoidal pattern. It is more reasonable that an airway decreases its diameter suddenly at the start of the deflation peroid, keeping the same size and the corresponding inertance value during the whole deflation peroid. Therefore, the upperbound of P_I calculated by Eq.(9). reflects a true P_I. On the contray, during the inflation period, the airways follow the sinusoidal pattern of applied HFV. In this case, approximately 20% overestimation is expected. Overall, at most 20% overestimation of P_I could be expected by taking its upperbound.

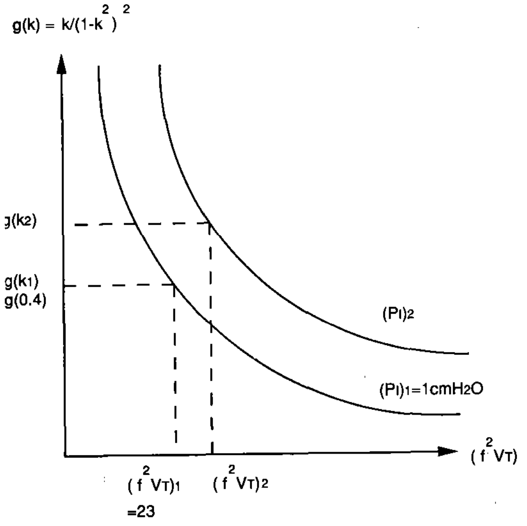

Fig. 1 Relationship between$(f^2\ V_T)$ and g(k), where $g(k)=k/(1-k^2)^2$ for a given(Pl) level
See text for explanation : if k=0.4 and Pl=1 cmH_2O, then$(f^2V_T)=23$

To extensively analyze the relationships between (P_I) and other variables, two figures are constructed in Figures 1 and 2. Given safety level of (P_I), (f^2V_T) and $g(K)=K/(1-K^2)^2$ are inversely related as shown in Figure 1. Figure 1 shows all combimations of (f^2V_T) and g(K) satisfying a constant (P_I). For example, when the safety level of P_I is I cmH_2O and K=0.4 (Broncho-constriction), (f^2V_T) value is calculated as 23 $1/s^2$. To maintain a constant f^2V_T. f^2 and V_T also have to be inversely related as shown in Figure 2. Since $f^2V_T=23$, has to be approximately 15 Hz if $V_T=0.1$ 1. In this case, the resultant minute ventilation is 90 1/min, which is an enough value for normal oxygenation. Therefore, no previously mentioned treatment is necessary prior to HFV application. This example demonstrates a possible algebraic steps to determine whether to treat a patient before applying HFV. However, applying these steps clinically requires variable values impossible to find from the patient such as K. Thus, it may be a reasonable recommendation that patients with airway disease should be paid a special attention and treated as mentioned previously prior to HFV application. The above usage of Figures 1 and 2 may be useful only as a decision advice.

LHI has been hypothesized to be mediated by various mechanisms, such as asymmetric resistance[4] or expiratory flow limitation[5]. The present study attempted to model the previously observed airway wall movement and relate it to asymmetric inertance, of in general, non-lineatr pressure-acceleration characteristics of the airways. Evidences have been reported previoulsly at high frequencies⁸⁾. When the pressure drop across the airways is experimentally studied, it is technically difficult to completely separate resistive and inertive pressure components, and the characteristics of airway inertance has been often ignored. The present study has a significance in that LHI was found to possibly occur due to asymmetric inertance during HFV and particularly important in patients with bronchoconstriction.

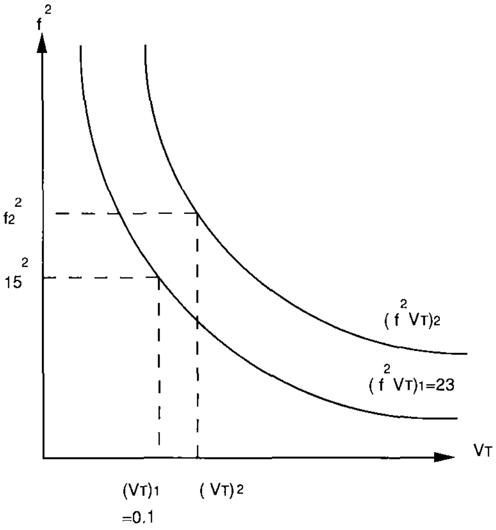

Fig. 2 Relationship between f^2 and V_T
See text for exeplanation : To satisfy (f^2 V_T) $=231/s^2$, $V_T=0.11$, $f=15Hz$

Ⅳ. CONCLUSION

Previously reported direct radiographic visualization data of airway movement were employed to model airway inertance as a possible asymmetric factor causing LHI during HFV. It was found that the asymmetry in airway inertance could result in a significant increase in mean lung volume, leading to LHI especially in patients with bronchoconstiction. It would be recommendable to treat those patients for bronchodilation prior to HFV application.

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