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Original Article

Mean Lung Pressure during Adult High-Frequency Oscillatory Ventilation: An Experimental Study Using a Lung Model

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In adult high-frequency oscillatory ventilation (HFOV), stroke volume (SV) and mean lung pressure (PLung) are important for lung protection. We measured the airway pressure at the Y-piece and the lung pressure during HFOV using a lung model and HFOV ventilators for adults (R100 and 3100B). The lung model was made of a 20-liter, airtight rigid plastic container (adiabatic compliance: 19.3 ml/cmH_2O) with or without a resistor (20 cmH_2O/l/sec). The ventilator settings were as follows: mean airway pressure (MAP), 30 cmH_2O; frequency, 5-15 Hz (every 1 Hz); airway pressure amplitude (AMP), maximum; and % of inspiratory time (IT), 50% for R100, 33% or 50% for 3100B. The measurements were also performed with an AMP of 2/3 or 1/3 maximum at 5, 10 and 15 Hz. The PLung and the measured MAP were not consistently identical to the setting MAP in either ventilator, and decreasing IT decreased the PLung in 3100B. In conclusion, we must pay attention to the possible discrepancy between the PLung and the setting MAP during adult HFOV.

Key words: HFOV, mean lung pressure, mean airway pressure

High-frequency oscillatory ventilation (HFOV) is a special mechanical ventilation mode which uses a small tidal volume (*i.e.*, stroke volume: SV) near or less than the anatomical dead space (≅2-3 ml/kg) and an extremely high respiratory rate (*i.e.*, frequency: f) of 3-15 Hz. Because the intra-alveolar pressure swings tend to be small, HFOV has been used as a lung protective ventilation mode for neonates suffering from respiratory distress syndrome [1, 2] and for children or adults suffering from acute respiratory distress syndrome (ARDS) [3-7].

Now two HFOV ventilators are available for use in adults, the R100 (Metran Co., Ltd., Kawaguchi, Japan) and SensorMedics 3100B (CareFusion, Yorba Linda, CA, USA). Recently, 2 large randomized controlled trials in ARDS adults which compared the HFOV with the conventional lung protective ventilation have been reported, one using R100 [8] and the other using 3100B [9]. However neither trial showed any survival benefits. Possible factors underlying this lack of efficacy were the size of the actual SV and the mean alveolar pressure, both of which are important to prevent ventilator-induced lung injury in ARDS adults but not routinely monitored clinically.

The performances of HFOV ventilators for adults,

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especially R100, have not been investigated vigorously. To our knowledge, there has been one bench study [10] that compared the actual SV of R100 and that of 3100B using a commercially available lung model and a position sensor. However, there have been no reports investigating the lung model pressure during HFOV with R100 or 3100B. In the present study, therefore, we investigated the lung model pressure under various settings using the two HFO ventilators.

Materials and Methods

Lung model. The lung model was made of a 20-liter, airtight rigid plastic container as previously described [11]. It was connected to the ventilator via an endotracheal tube (ETT) with an 8.0 mm ID and 32.0 cm length (Fig. 1). This lung model had a static compliance of 19.3 ml/cmH_2O (*i.e.*, 20 l/760 mmHg) due to gas compression and expansion. R100 or 3100B was used as the HFOV ventilator under the dry condition with the following settings: constant fresh gas flow (base flow: BF), 30 l/min; mean airway pressure (MAP), 30 cmH_2O; and fraction of inspired oxygen, 0.21. A resistor of 20 cmH_2O/l/sec was placed or not placed between the lung model and the ETT.

Measurement of airway pressure and lung model pressure. The airway pressure at the Y-piece and the lung model pressure were measured using a PF-300 flow analyzer (IMT Medical, Buchs, Switzerland) with the following additional settings: frequency, 5-15 Hz (every 1 Hz); airway pressure amplitude (AMP) indicated on the panel, maximum; and % inspiratory time (IT), 50% for R100, 33% and 50% for 3100B. The measurement was repeated 5 times. The pressure waveform measured by PF-300 was monitored on a personal computer using an exclusive software program and recorded with several settings.

Statistical analysis. All values were expressed as the mean ± standard deviation (m ± SD). Statistical analysis was done using analysis of variance (ANOVA) followed by Tukey's test. P values less than 0.01 were considered to be significant.

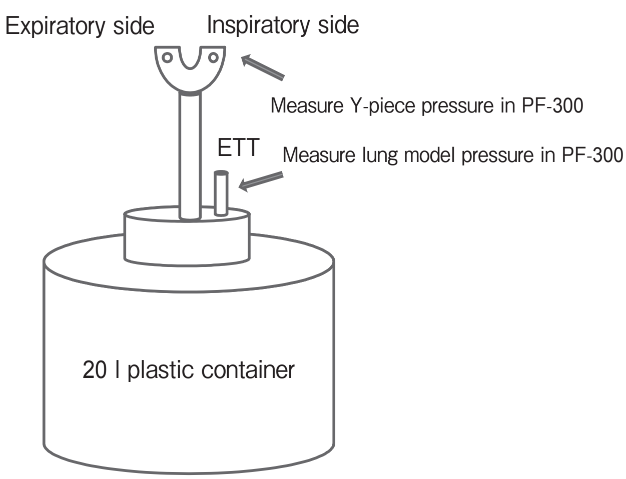

Fig. 1 Schema of the experimental setting. The experimental setting is presented schematically. The lung model was connected via an 8-mm ID endotracheal tube to the ventilator circuit. The lung model pressure and the airway pressure were measured by PF-300.

Results

Table 1 shows the measured MAP at the Y-piece and the mean pressure of the lung model (PLung) with all frequencies together. The measured MAP with all frequencies together was slightly lower than the setting of MAP in R100 and it was 4-5 cmH_2O lower than that in 3100B. The measured MAP and the PLung both with all frequencies together were not always identical in both ventilators. Fig. 2 shows the measured MAP and the PLung at each frequency. The measured MAP was consistently lower than the setting MAP at all frequencies in R100 without a resistor and with all settings in 3100B. The PLung was consistently close to the measured MAP in R100 with all settings but not in 3100B.

Table 1 Measured MAP and PLung at all frequencies (5-15 Hz) together

		measured MAP	PLung
R100:	IT = 50% R = 0	28.0 ± 1.0	27.2 ± 1.1*
	IT = 50% R = 20	29.6 ± 0.7	29.9 ± 0.7
3100B:	IT = 50% R = 0	26.4 ± 0.7	28.5 ± 1.5*
	IT = 50% R = 20	25.0 ± 0.6	25.3 ± 1.6
	IT = 33% R = 0	26.3 ± 0.9	24.4 ± 2.2*
	IT = 33% R = 20	25.1 ± 1.2	18.7 ± 3.0*

mean ± SD (cmH_2O), n = 55 trials, MAP, mean airway pressure; Plung, measured mean pressure of lung model; IT, inspiratory time; R, resistance (cmH_2O/l/sec).
*: $p < 0.001$ compared to measured MAP

Table 2 Measured AMP and setting AMP at all frequencies (5–15 Hz) together

		measured AMP	setting AMP
R100:	IT=50% R=0	130.7 ± 3.5*	96.6 ± 12.5
	IT=50% R=20	149.6 ± 9.2*	120.7 ± 23.9
3100B:	IT=50% R=0	143.8 ± 11.6*	81.3 ± 2.3
	IT=50% R=20	170.5 ± 5.1*	119.3 ± 7.8
	IT=33% R=0	138.3 ± 4.3*	79.2 ± 1.5
	IT=33% R=20	173.6 ± 4.3*	118.8 ± 5.0

mean±SD (cmH_2O), n = 55 trials, AMP, airway pressure amplitude; IT, inspiratory time; R, resistance (cmH_2O/l/sec).
*: $p < 0.001$ compared to setting AMP

Table 2 shows the measured AMP at the Y-piece and the setting AMP indicated on the panel of the ventilator with all frequencies together and Fig. 3 shows those at each frequency. The measured AMP was consistently higher than the setting AMP with all settings in both ventilators. Fig. 4 shows the typical airway pressure waveforms recorded at the Y-piece.

Discussion

We investigated the lung model pressure during HFOV with R100 and 3100B. As we know, this is the first study that investigated the lung model pressure using adult HFOV ventilators. We also investigated the airway pressure at the Y-piece. Because the IT is fixed at 50% in R100 and it can be changed between 30% and 50% in 3100B, R100 was used with an IT of 50% and 3100B was used with an IT of 33% or 50% in our study. Usually clinicians use adult HFOV ventilators supposing or expecting that both the PLung and the MAP measured at the Y-piece are identical to the setting MAP. However, our study showed different results. In regard to the PLung and the measured airway pressure, 2 main points merit further discussion: 1) the discrepancy between the measured MAP and the Plung; and 2) the discrepancy between the measured MAP or AMP and the setting MAP or AMP.

At first, the discrepancy between the measured MAP and the PLung was consistently less than 1.5 cmH_2O in R100 with all settings but was evident in 3100B with several settings. During HFOV with the airway pressure waveform of a sine curve (*i.e.*, IT 50%), the PLung is supposed to be identical to the MAP measured at the Y-piece [12]. However, in our study the airway pressure waveforms recorded at the Y-piece were different from sine curves even with an IT of 50%. The pressure waveform of 3100B recorded at 5 Hz was rather square, as previously reported in 3100A (CareFusion, Yorba Linda, CA, USA), an HFOV ventilator for infants and children [13]. We suggest that the discrepancy between the measured MAP and the PLung occurs if the airway pressure waveform during inspiration and that during expiration are not quite symmetrical. In 3100B, the PLung with the IT of 33% was much lower than that with the IT of 50% at all frequencies. Pillow *et al.* [14] have reported a similar phenomenon using 3100A and 3.0 mm ID ETT. With an IT of 33%, the expiration might initially be greater than the inspiration due to the longer expiration time, and then the lung volume and the PLung might decrease. After that, the inspiration and the expiration might be balanced at decreased PLung. Furthermore, our study showed that increasing frequency—namely, shortening of the cycle time or increasing airway resistance—might emphasize this phenomenon. 3100B has been used mainly with an IT of 33% in clinical situations to avoid the risk of gas trapping [4, 8], and we did observe that the PLung was higher than the setting MAP at 5–6 Hz with an IT of 50% and without a resistor. However, we cannot recommend the use of an IT of 33% from our results, especially at higher frequencies and with increased resistance. Recently, Mentzelopoulos *et al.* [15] reported that the mean tracheal pressure in ARDS adults was 6–7 cmH_2O lower than the setting MAP using 3100B with a frequency of 4 Hz and an IT of 33%. This might explain that the recent large randomized clinical trial [9] using 3100B with an IT of 33% showed no improvement of oxygenation in the HFOV group compared to the control group.

Secondly, the discrepancy between the measured MAP and the setting MAP was greater than 2 cmH_2O in R100 at 10–14 Hz without a resistor and in 3100B with all settings. In addition, the measured AMP was consistently greater than the setting AMP in both ventilators with all settings. Although R100 indicates the airway pressure waveform on the panel, the indicated waveform was much smoother than that we recorded. We measured the airway pressure at the proximal side of the Y-piece, while both ventilators

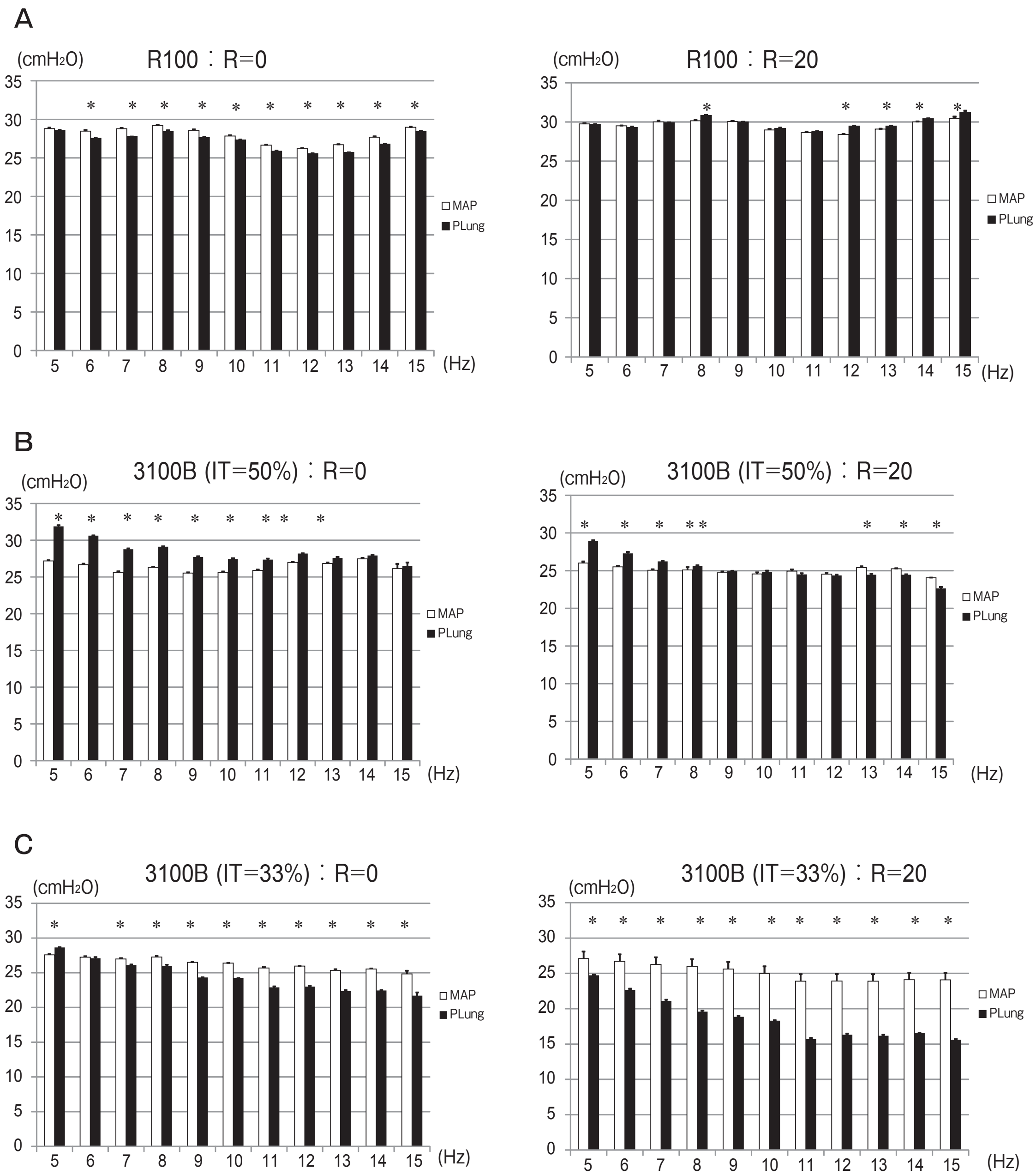

Fig. 2 Mean airway pressure (MAP) measured at the Y-piece and mean lung model pressure (PLung). **A**, R100 (IT = 50%); **B**, 3100B (IT = 50%); **C**, 3100B (IT = 33%) (n = 5 trials). $^{*}p < 0.001$, $^{**}p < 0.01$. IT, inspiratory time; open bar: mean airway pressure (MAP), closed bar: mean lung model pressure (PLung).

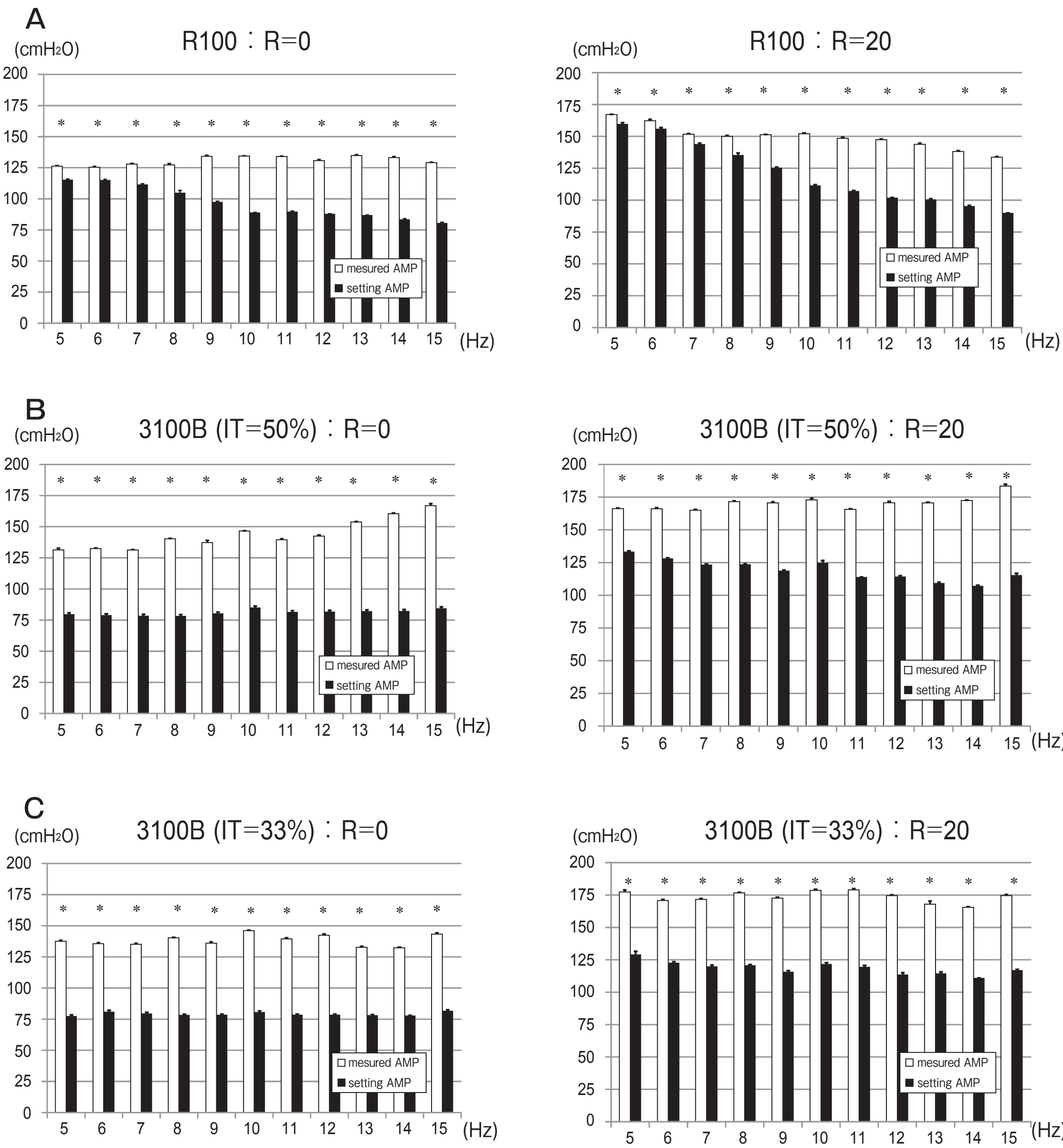

Fig. 3 Airway pressure amplitude (AMP) measured at the Y-piece and indicated on the panel of the ventilator. **A**, R100 (IT = 50%); **B**, 3100B (IT = 50%); **C**, 3100B (IT = 33%) (n = 5 trials). $^*p < 0.001$. IT, inspiratory time, open bar: AMP measured at the Y-piece by PF-300, closed bar: AMP indicated on the panel of the ventilator.

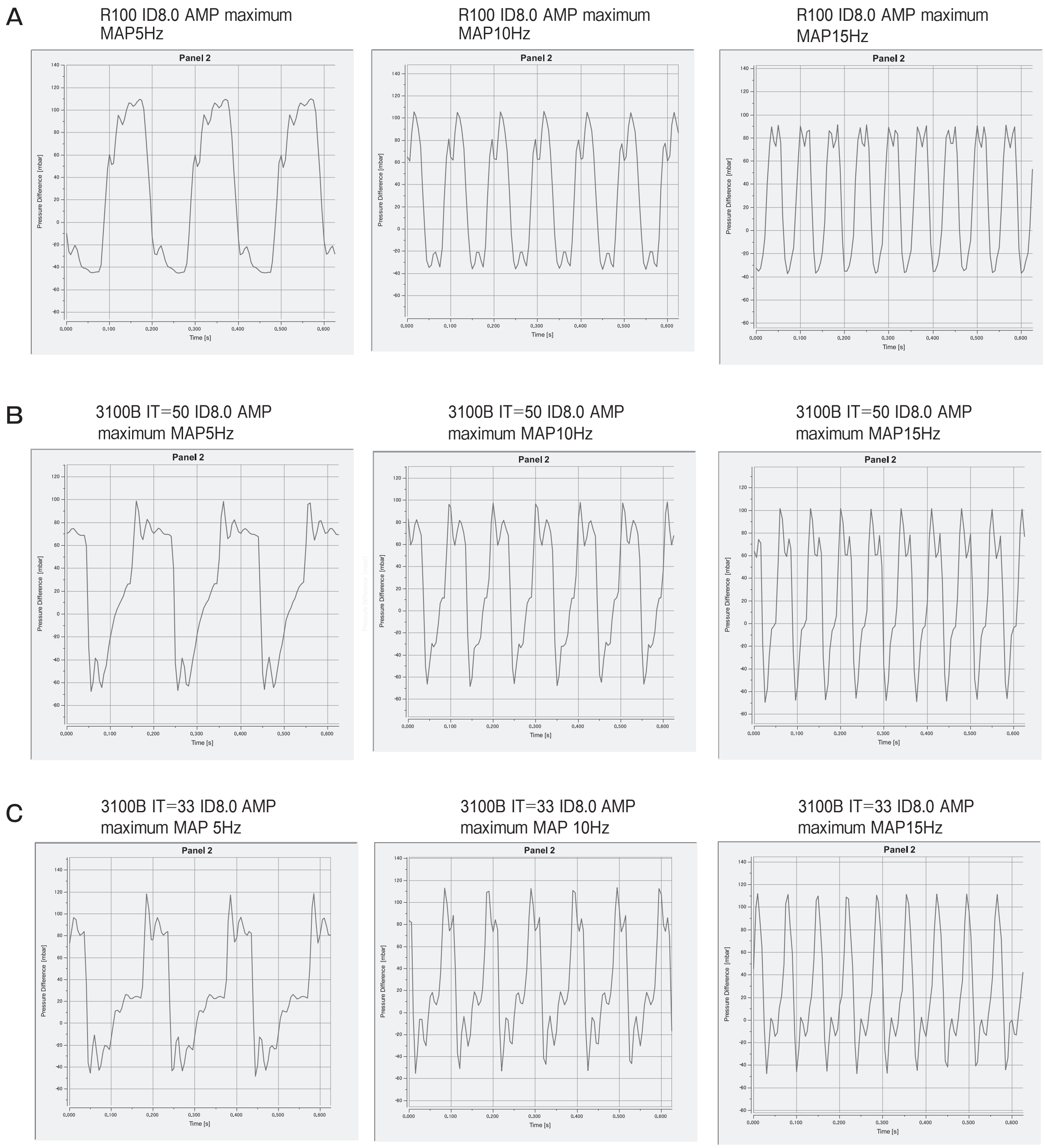

Fig. 4 Examples of the airway pressure waveforms recorded at the Y-piece. A, R100 (IT = 50%); B, 3100B (IT = 50%); C, 3100B (IT = 33%).

measured it at the distal side. This might be one reason for these discrepancies. However, we cannot exclude the possibility that the airway pressure is not precisely measured by the ventilator. Because the ventilator cannot be used safely unless the MAP is controlled precisely, we hope that the manufacturers will examine this issue.

In summary, the PLung and the measured MAP at the Y-piece were not consistently identical to the setting MAP either in R100 or 3100B, and decreasing IT decreased the PLung in 3100B. Therefore we must pay attention to the possible discrepancy between the PLung and the setting MAP during adult HFOV.

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