Advanced Training in Neonatal/Perinatal Medicine

EXAMPLE PROJECT

PROJECT TITLE: Dräger VN500's oscillatory performance has a frequency dependent threshold

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Abbreviations

C_{RS}	Respiratory system compliance
ETT	Endotracheal tube
Fr	Frequency
HFOV	High-frequency oscillatory ventilation
Hz	Hertz
I:E	Inspiratory to expiratory ratio
MAP	Mean airway pressure
ΔP	Oscillatory change in pressure
P_{AO}	Pressure at the airway opening
P_{TRACH}	Pressure in the 'trachea' of the test lung
P_{VENT}	Pressure in the ventilator
R_{RS}	Respiratory system resistance
SM3100	Sensormedics 3100 high-frequency oscillator
V'_{AO}	Flow at the airway opening
VN500	Dräger VN500 high-frequency oscillator
V_{THF}	High-frequency tidal volume at the airway opening

What is already known on this topic?

- Safe and effective application of high frequency ventilation requires an understanding of the performance characteristics of the ventilator being used.
- High-frequency ventilators demonstrate differences in their performance characteristics. Some older ventilators are known to have a frequency related limitation in pressure amplitude and tidal volume.

What this paper adds?

- In the benchtop setting, the Dräger VN500 demonstrates a frequency related reduction in oscillatory pressure amplitude not observed in the Sensormedics 3100.
- Increasing the frequency of oscillations resulted in a greater reduction in delivered high-frequency tidal volume in the Dräger VN500 compared with the Sensormedics 3100.
- Clinicians need to be aware of these differences and may need to adapt their ventilation strategies accordingly.

Abstract

Background: The high-frequency pressure amplitude (ΔP) of the Dräger BabyLog 8000 High-frequency ventilator is related to the frequency, and clinical application differs from other high-frequency devices. The performance characteristics of the new VN500 ventilator have not been described.

Aim: To compare the high-frequency pressure amplitude (ΔP) and tidal volume (V_{THF}) delivered by the Dräger VN500 and the Sensormedics 3100 (SM3100) through a range of oscillatory frequencies.

Methods: In this benchtop study high-frequency oscillations were applied to an infant test lung at unrestricted set amplitudes. Pressure and flow were measured as a function of frequency, incremented by 1 Hz from 5 to 15 Hz. Measurements were repeated for a range of ventilator settings, and lung resistive and compliance states.

Results: The VN500, but not the SM3100, demonstrated an exponential decrease in airway opening ΔP as frequency increased. The difference between the SM3100 and VN500 delivered V_{THF} became greater with each frequency increment. At 15Hz, VN500 V_{THF} was 49% of SM3100 V_{THF}.

Conclusions: The VN500 demonstrates a frequency related reduction in ΔP not observed in the SM3100. Clinicians need to be aware of these differences in performance characteristics.

Abstract word count: 186 words

INTRODUCTION

High-frequency oscillatory ventilation (HFOV) is commonly used in neonatal intensive care units. The mechanism of gas exchange during HFOV is complex[1] and may vary according to the method of generation and attenuation of the pressure waveform[2-4].

The Sensormedics 3100 (SM3100; CareFusion, San Diego, CA) and BabyLog 8000+ (Drägerwerk Ag & Co., Lübeck, Germany) have been in wide use for more than two decades. The SM3100 uses a piston-diaphragm, where as the BabyLog 8000+ uses a Venturi system to generate oscillatory pressure amplitudes (ΔP) and resultant tidal volumes. In the BL8000+, a frequency dependent maximum ΔP threshold is known to exist[5]. Consequently, different settings are required when ventilating with the BabyLog 8000+ compared with the SM3100. Lower frequencies are used in order to deliver tidal volumes capable of maintaining adequate gas exchange. The VN500 ventilator superseded the BabyLog 8000+ in 2010, reportedly with a more powerful venturi system. The relationship between applied frequency, ΔP and tidal volume for the VN500 have not previously been reported.

The aims of our benchtop study were 1) to determine whether there were differences in the maximal ΔP and tidal volume that could be generated through a range of frequencies and lung compliance and resistance states using the VN500, and 2) compare these with the performance characteristics of the SM3100.

METHODS

Experiment Setup

This study was performed using a variable compliance (C_{RS}; minimum 1.0 mL/cm H_2O) infant test lung (model 560li, Michigan Instruments, Grand Rapids, MI). Each device was attached via the manufacturer's recommended circuit (VN500; Dräger VentStar Heated N circuit, and SM3100; Carefusion flexible patient circuit) to an uncuffed 2.5mm or 3.5mm endotracheal tube (ETT) trimmed to 15 cm and attached to the test lung to make a leak free system. To minimize the variable effect of humidity, on resistance and ΔP, the humidifier block was removed from the circuits.

Measurements

The experimental arrangement is shown in Figure 1. Airway pressure was measured using pressure transducers (1000Hz; SC-24, SCIREQ, Montreal, Canada) located at the proximal end of the inspiratory limb of the ventilator circuit (P_{VENT}), proximal to the ETT at the airway opening (P_{AO}) and from a dedicated pressure port within the test lung (P_{TRACH}). Flow ($\dot{V}_{AO}$) and tidal volume (V_{THF}) were measured using a hot wire anemometer (200Hz; Florian respiration monitor, Acutronic Medical Systems, Zug, Switzerland) located at the airway opening[6].

Experiment Protocol

For both the SM3100 and VN500, ventilation was applied with a set ΔP of 90 cm H_2O (maximum setting for VN500) and frequency (Fr) increased in 1 Hz increments every 5 minutes from 5 to 15 Hz. This was performed for all permutations of inspiratory to expiratory ratio (I:E) 1:2 and 1:1, and test lung C_{RS} 1.0 and 2.0 mL/cm H_2O . Airway resistance (R_{RS}), was varied by using a 3.5 mm ETT with a mean airway pressure (MAP) of 20 cm H_2O, and a 2.5 mm ETT (MAP 10 cm H_2O).

Data Analysis

Pressure and flow signals were digitized using LabChart 7.2 (ADInstruments, Sydney, Australia). The amplitude (Δ) of the P_{VENT}, P_{AO} and P_{TRACH} waveforms was calculated for the last 300 stable consecutive oscillations at each recording. Each parameter was graphed against frequency and the relationship examined to determine the best linear or non-linear model using Prism V4.02 (GraphPad, San Diego, CA). The simplest model in which all coefficients of determination (R^2) were significant ($p<0.05$) was deemed representative, and a $R^2>0.7$ defined as a good fit of the model.

RESULTS

For the VN500, but not SM3100, ΔP_{VENT} decreased exponentially as the Fr was increased from 5 to 15 Hz despite a constant ventilator ΔP set at 90 cm H_2O (Figure 2), irrespective of I:E ratio, MAP and ETT size permutations; all $R^2>0.95$. The SM3100 maintained a stable ΔP_{VENT} approximating the set ΔP at all Fr examined. I:E ratio exerted the greatest influence on the absolute ΔP_{VENT} at each Fr in the VN500. At 15 Hz with a I:E ratio of 1:2, C_{RS} 1.0 mL/cm H_2O and ETT 2.5mm, the maximum ΔP_{VENT} recorded was 34.2 cm H_2O, compared with 41.3 cm H_2O using I:E 1:1, C_{RS} 2.0 mL/cm H_2O and ETT 3.5mm (Supplemental Digital Content Figure 1). The relationship between frequency and ΔP_{VENT} was similar at different C_{RS} and R_{RS} permutations, except at test lung C_{RS} of 1.0 mL/cm

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H_2O and the lower R_{RS} (3.5 ETT). At these settings, ΔP_{VENT} was 4 to 10 cm H_2O higher than the other permutations between frequencies of 7 to 13 Hz in the VN500.

Figure 3 shows the relationships between Fr and ΔP_{AO} and V_{THF} using the same permutations as Figure 2. A similar exponential decrease in ΔP_{AO} in the VN500 was seen (R^2 >0.97). There was no change in ΔP_{AO} with the SM3100. Both devices had a similar pattern of frequency related decrease in V_{THF}. As Fr was increased, the difference in absolute V_{THF} between the SM3100 and VN500 became incrementally greater (Supplemental Digital Content Figure 2). By 15 Hz, the V_{THF} delivered by the SM3100B was almost twice that of the VN500. The difference in ΔP_{TRACH} between the two oscillators as the frequency was increased was similar to that of V_{THF} (Supplemental Digital Content Figure 3), with the potential of the VN500 ΔP_{TRACH} being at least 40% less than the SM3100B at frequencies of 10 Hz or more (Figure 4 and Supplemental Digital Content Figure 4).

DISCUSSION

In this benchtop study, we found that there was a difference between the new VN500 and SM3100 with regards to the delivered V_{THF} and ΔP at various points in the respiratory circuit that became more marked as the frequency was increased. I:E ratio, C_{RS} and R_{RS} influenced the magnitude of changes observed. Our results are a guide to the theoretical maximum ΔP that could be generated at any given frequency. To our knowledge, this is the first report of the ΔP performance characteristics of the VN500 in HFOV mode.

The performance characteristics of the SM3100 have been well described previously, and our results are consistent with these studies[3,5,7,8]. The pattern of performance characteristics we observed in the VN500 shows similarities to those of the BL8000[5]. The VN500 was able to generate larger V_{THF} at higher frequencies than those reported for the BL8000[5], but these were still closer to the BL8000 than the SM3100. The relationship between set ΔP and ΔP_{VENT} suggests that the frequency dependent relationship we observed relates to the similarities in the underlying mechanism used to generate HFOV in the two Dräger devices, both of which use a Venturi-assisted expiration system as opposed to a piston diaphragm (SM3100). The Venturi system has been attributed to the performance differences in the BL8000. It seems likely that same, albeit more powerful, Venturi-assisted expiration system accounts for the results we observed in the VN500.

Alveolar ventilation during HFOV is determined by the product of the frequency and the square of V_{THF}, with V_{THF} representing the stroke volume of the pressure amplitude[9,10]. The square relationship between alveolar ventilation and V_{THF} suggests that the difference in alveolar ventilation between these two devices is likely to be even greater. Further studies are required to determine whether our findings translate to significant differences in carbon dioxide removal at higher frequencies.

The optimal set frequency is determined by the pathophysiology and resultant time constant of the lung[11]. Unlike the SM3100, there appears to be limits in the ΔP that the VN500 could be expected to achieve at certain frequencies. In Australasia, HFOV is used for those infants with the most severe respiratory failure[12]. In these situations, clinicians may need to decrease frequency and/or increase I:E ratio with the VN500 to achieve adequate ΔP and V_{THF} for CO_2 removal. Clinicians need to be aware that unlike conventional ventilation where settings are largely interchangeable between ventilators, in HFOV devices the settings are unique to the device and are not transferable.

We chose a ΔP of 90 cm H_2O, well above settings being used clinically, to allow unrestricted performance of the oscillator. This was intentional, as this is the first report of the performance characteristics of the VN500. Choosing a lower ΔP setting may have applied an external limitation on performance, and misrepresented the inherent technical capabilities of each device. By allowing unrestricted performance of the high-frequency power we were also able to inform the clinician of the theoretical maximum ΔP that could be expected from the VN500 at any given frequency. It is likely that other more variable factors, such as leak, water in the circuit (humidification), spontaneous respiratory effort and nature of lung pathology would exert a negative rather than positive effect on our findings.

This study has a number of limitations. This was a benchtop study and the findings may not be clinically transferable. Minimum simulated C_{RS} was limited to 1.0 mL/cm H_2O, greater than in severe lung disease. Differences in patient circuits can attenuate high-frequency oscillations; the rigid SM3100 circuit has low R_{RS}, and differs from the VN500 circuit. Nonetheless, some of the frequency related performance characteristics we observed were also noted upstream from the circuit. This suggests that our findings relate to the inherent operational characteristics of these devices.

Conclusions

Like the BL8000, set frequency and I:E ratio determine the maximum ΔP available in the VN500. Clinicians need to be aware of the properties of their high-frequency ventilators and adapt their ventilation strategies accordingly.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge [redacted] and [redacted] for advice on this study, Dräger Medical for use of the Dräger VN500.

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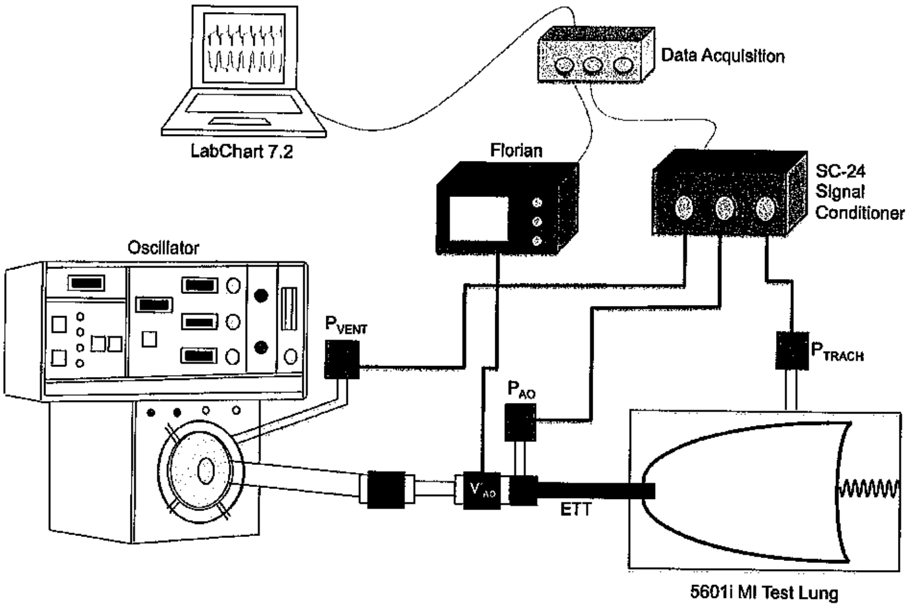
FIGURE LEGENDS

Figure 1. Schematic diagram of the experimental setup. Pressure transducers are shown as dark grey squares. Flow (V'_{AO}; black square) was measured at the airway opening between the ETT and the ventilator hot wire anemometer (VN500) or sham anemometer (SM3100B).

Figure 2. Relationship between frequency and ΔP_{VENT} for the SM3100 (diamonds) and VN500 (circles) at 1:1 (closed symbols and dashed lines) and 1:2 (open symbols and solid lines) I:E ratio. Data shown for a test lung C_{RS} of 1.0 mL/cm H_2O, ETT 2.5mm and mean airway pressure 10 cm H_2O. Other permutations are provided in the online supplemental material.

Figure 3. A. Relationship between frequency and ΔP_{AO} for the SM3100 (diamonds) and VN500 (circles) at a test lung C_{RS} of 1.0 mL/cm H_2O and 2.5 mm ETT. **B.** Relationship between frequency and V_{THF} for the SM3100 (triangles) and VN500 (squares) at the same settings. For both relationships data is shown for I:E ratios of 1:1 (closed symbols and dashed lines) and 1:2 (open symbols and solid lines). There was no difference in the relationships for the other permutations with a 2.5 mm ETT. The 3.5 mm ETT data is available in the online supplemental material.

Figure 4. Percentage difference in ΔP_{TRACH} generated by the SM3100 and VN500 at different frequencies in a test lung with C_{RS} 1.0 mL/cm H_2O and 2.5 mm ETT. Closed circles represent data for I:E ratio of 1:1 and open circles 1:2.



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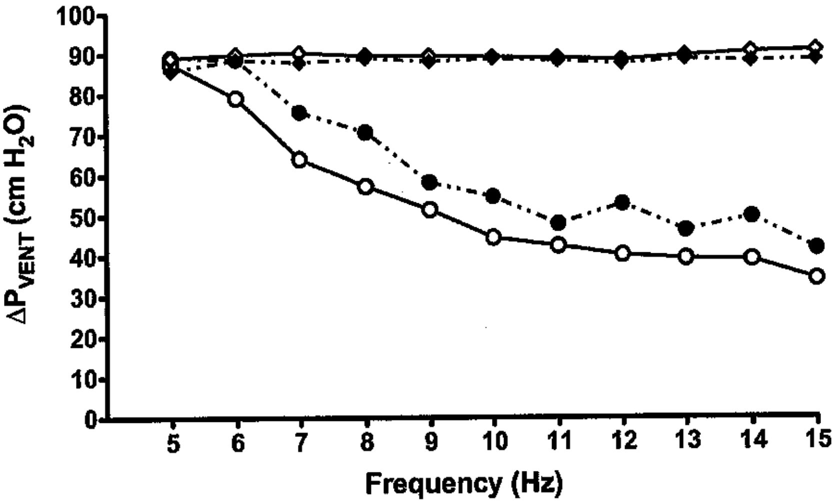

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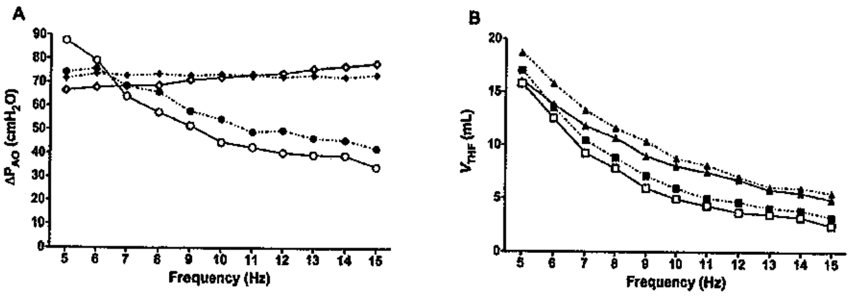

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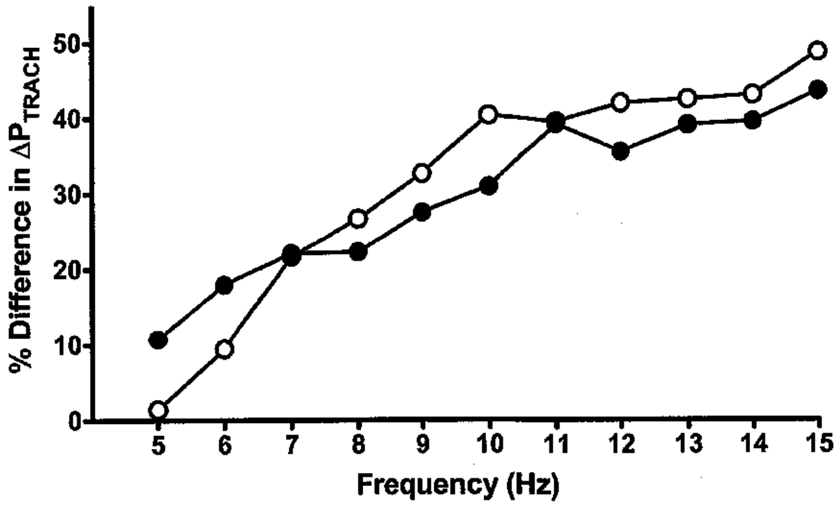

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ONLINE SUPPLEMENTAL MATERIAL

OSM Figure 1. Relationship between frequency and ΔP_{VENT} for the SM3100 (red) and the VN500 (blue) for ETT sizes 2.5mm (circles; **Panels A and C**) and 3.5mm (squares; **Panels B and D**) at a test lung C_{RS} of 1.0 mL/cm H_2O (open circles and squares) and C_{RS} 2.0 mL/cm H_2O (filled circles and squares). **Panels A and B** shows data using an I:E ratio 1:2 and **Panels C and D** I:E ratio 1:1.

OSM Figure 2. Relationship between frequency and V_{THF} for the SM3100 (red) and the VN500 (blue), both at I:E ratio 1:2, for ETT sizes 2.5mm (circles; **Panel A**) and 3.5mm (squares; **Panel B**). Test lung C_{RS} set at 1.0 mL/cm H_2O (open circles and squares) and 2.0 mL/cm H_2O (filled circles and squares).

OSM Figure 3. Percentage difference in V_{THF} generated by the SM3100 and VN500 at different frequencies in a test lung with C_{RS} 1.0 mL/cm H_2O for a 2.5 mm ETT. Closed triangles represent data for I:E ratio of 1:2 and open triangles 1:1.

OSM Figure 4. Relationship between frequency and ΔP_{TRACH} for the SM3100 (red) and the VN500 (blue) at a test lung C_{RS} of 1.0 mL/cm H_2O (open circles) and C_{RS} 2.0 mL/cm H_2O (filled circles) with a 2.5 mm ETT. Data from Figure 3 represents the differences in ΔP_{TRACH} at each frequency between SM3100 and VN500.

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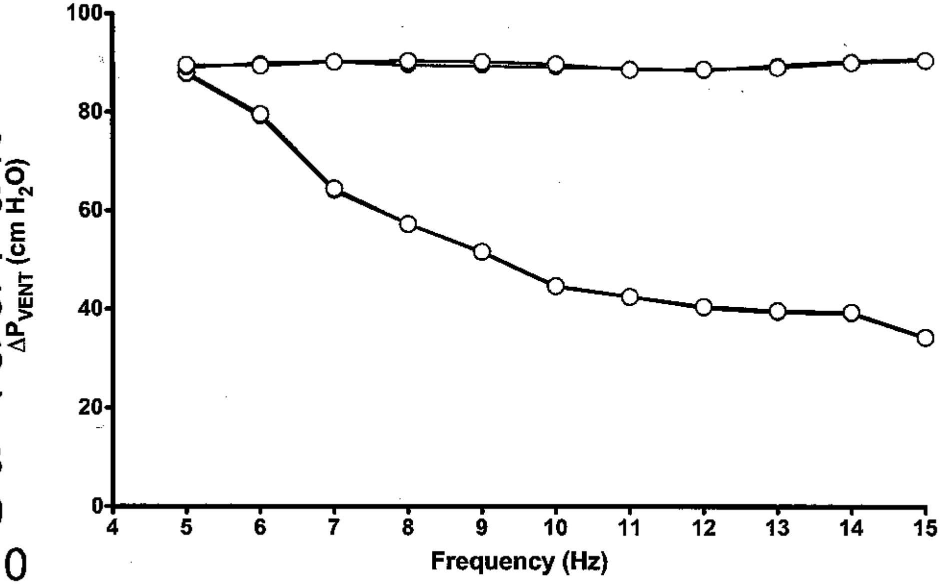
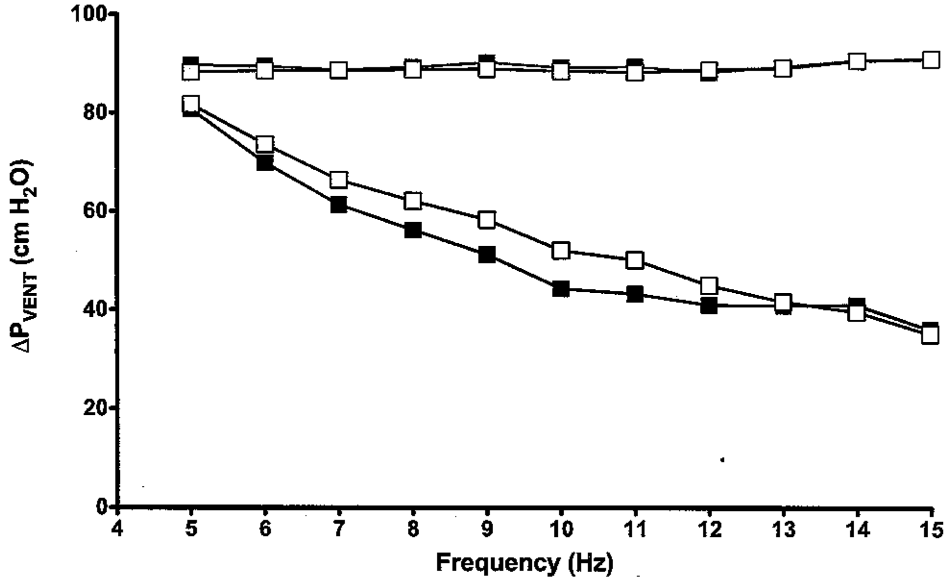
OSM Figure 1 Panel A



OSM Figure 1 Panel B



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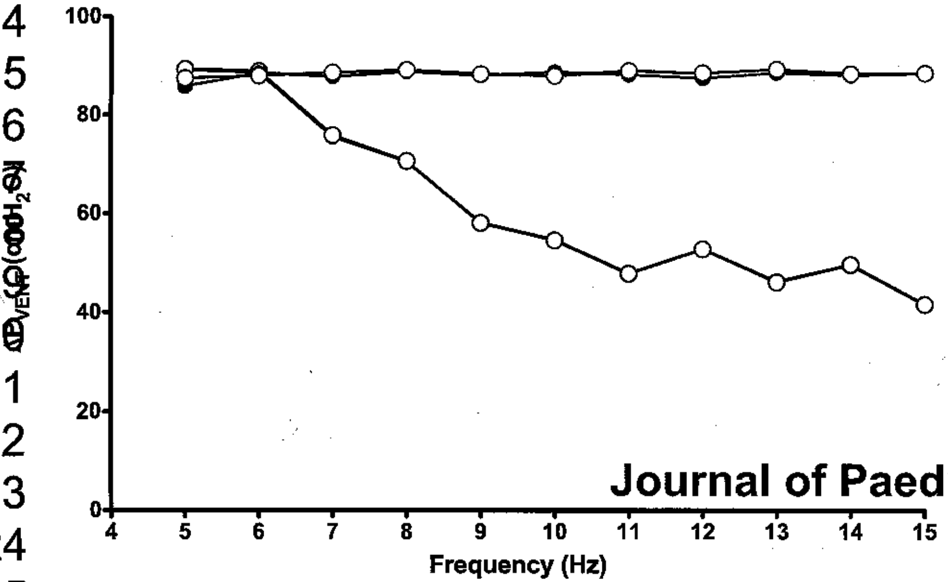

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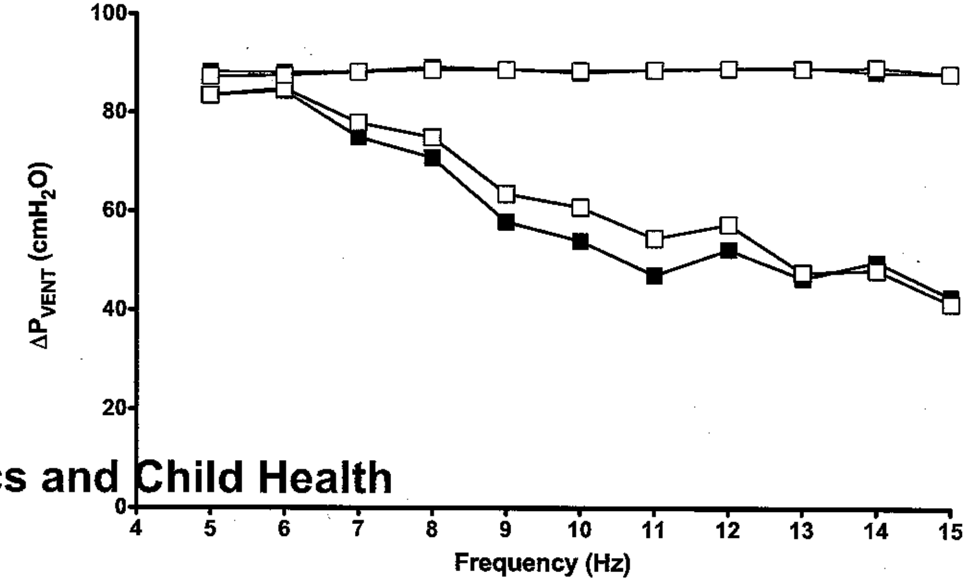

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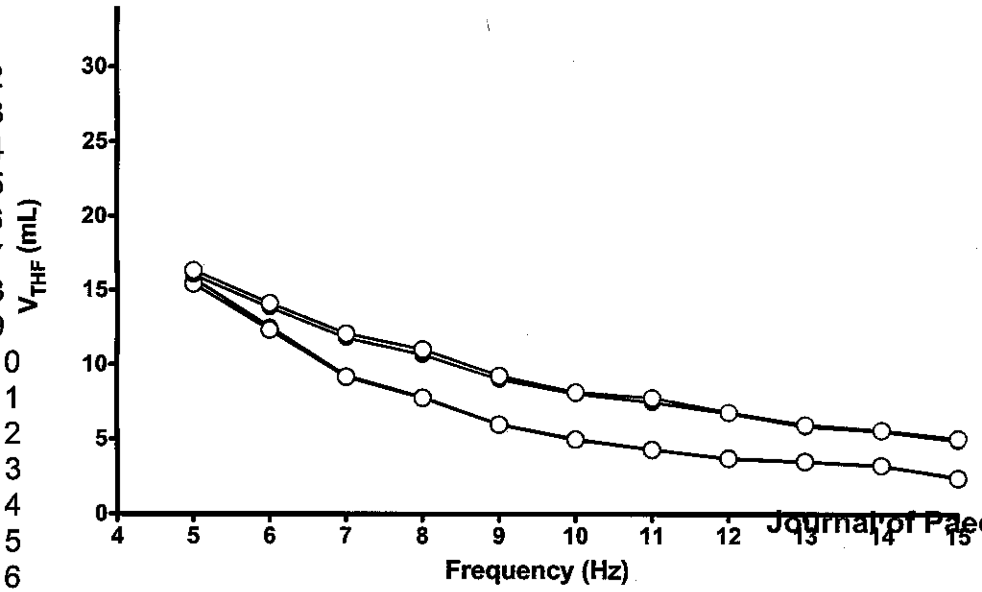
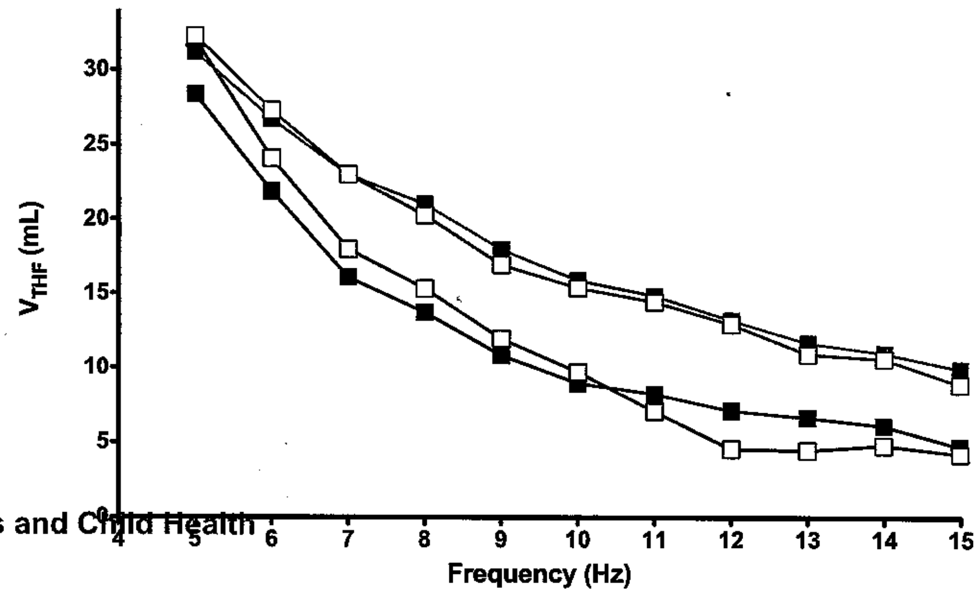
OSM Figure 2A



OSM Figure 2B



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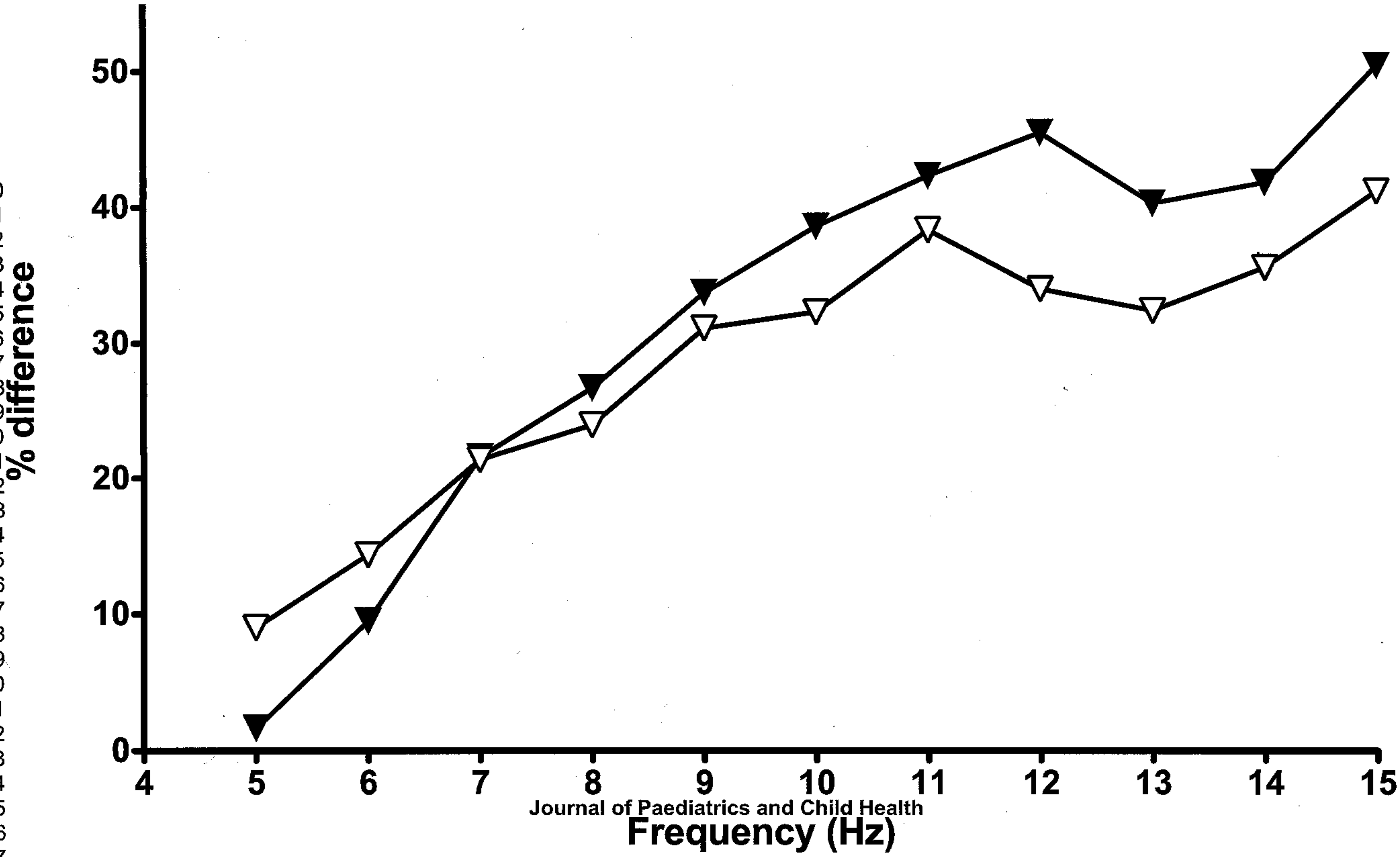
OSM Figure 3



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OSM Figure 4