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Experimental Model of Laryngotracheal Stenosis in Infants: Effects of Different High-frequency Jet Ventilation Patterns on Pulmonary Parameters

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Key Words:	techniques < Airway, difficult < Airway, infant < Age



Fig. 1: Modified Kleinsasser laryngoscope for supraglottic, superimposed HFJV (C. Reiner, Vienna, Austria). The jet nozzles are permanent integrated in the wall of the jet laryngoscope, therefore no dislocation or deviation of the jet stream is possible.

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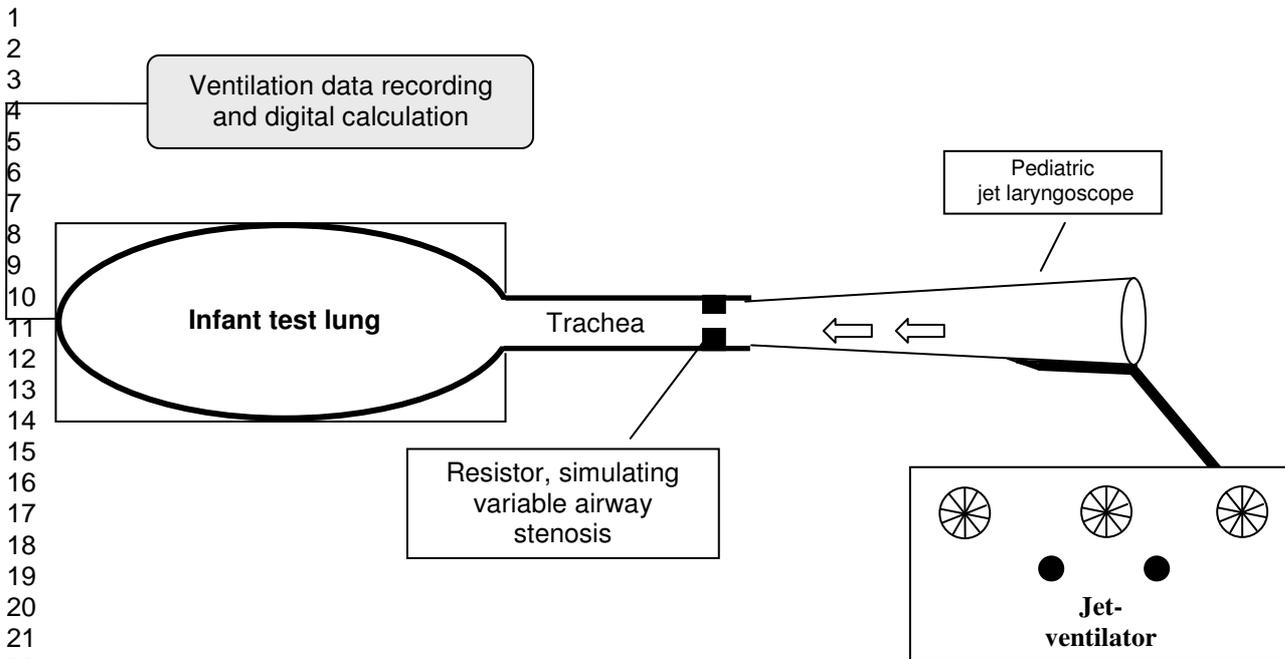


Fig. 2: Infant trachea – lung model. Ventilation was performed as supraglottic (suprastenotic) HFJV via modified jet laryngoscope for children with integrated nozzels. Arrows show the direction of the jet stream.

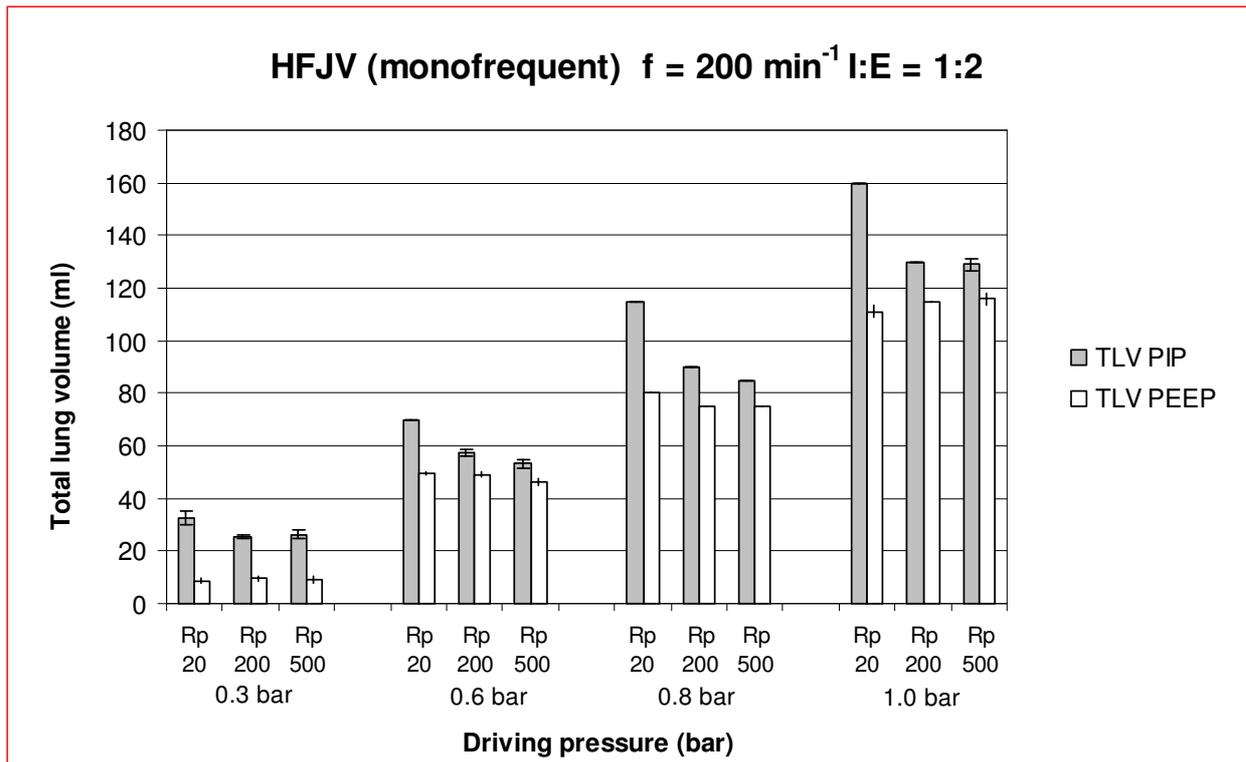


Fig. 3: Total lung volumes (TLV) during supraglottic monofrequent HFJV (frequency 200 min^{-1} , I:E 1:2) in various driving pressures and diameters of stenosis at peak inspiratory pressure (PIP) level and at positive end-expiratory pressure (PEEP) level.

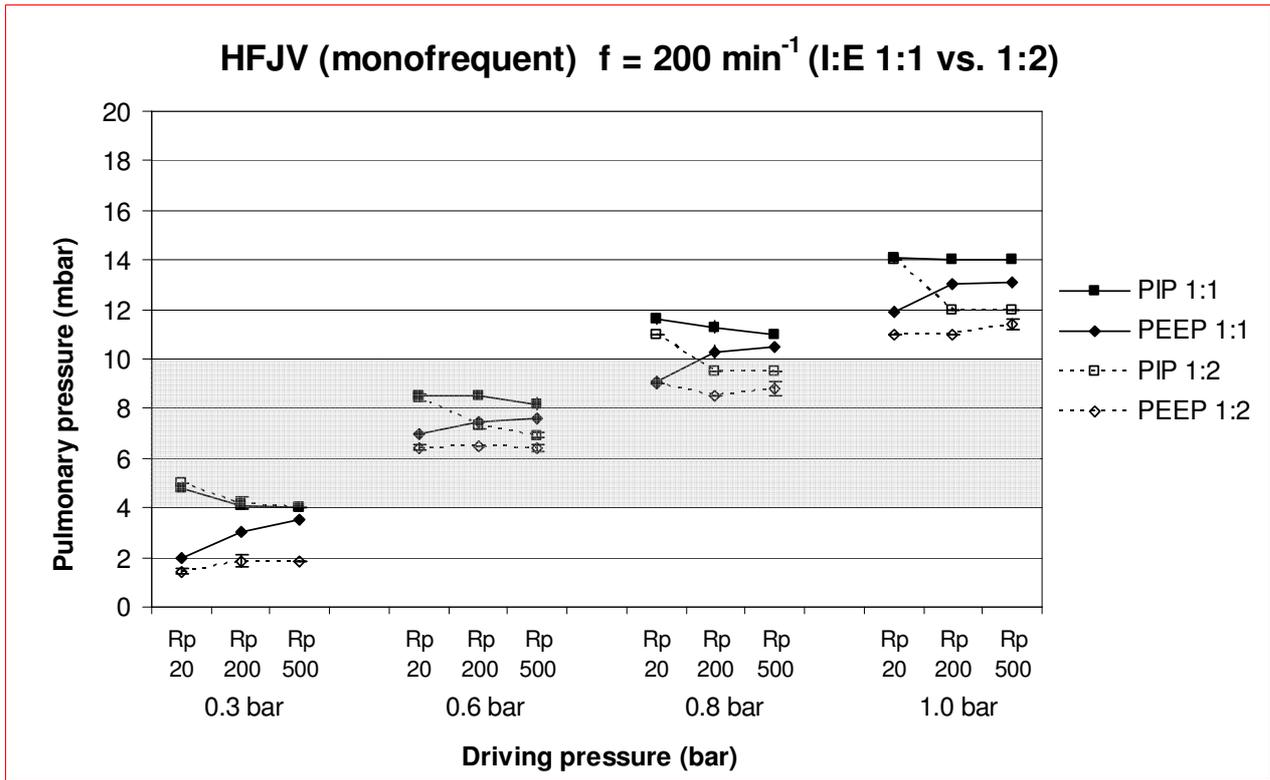


Fig. 4: Pulmonary pressures (mbar) during supraglottic monofrequent HFJV (frequency 200 min^{-1} , I:E 1:1 vs 1:2) in various driving pressures and diameters of stenosis: peak inspiratory pressure (PIP) and positive end-expiratory pressure (PEEP). The marked area represents clinically adequate PEEP levels in ventilation of newborns and infants.

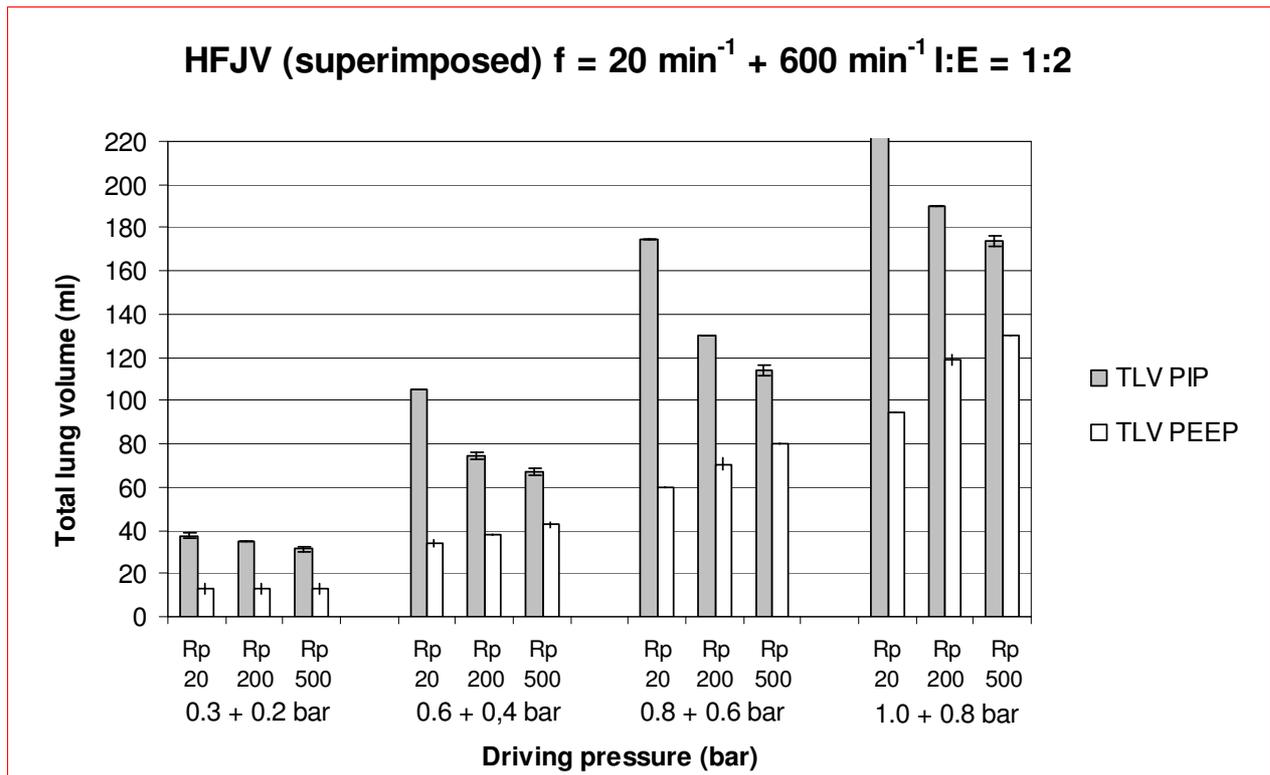


Fig. 5: Total lung volumes (TLV) during supraglottic, superimposed HFJV (frequency: 20 min^{-1} respectively 600 min^{-1} , I:E 1:2) with various driving pressures and diameters of stenosis at peak inspiratory pressure (PIP) level and at positive end-expiratory pressure (PEEP) level.

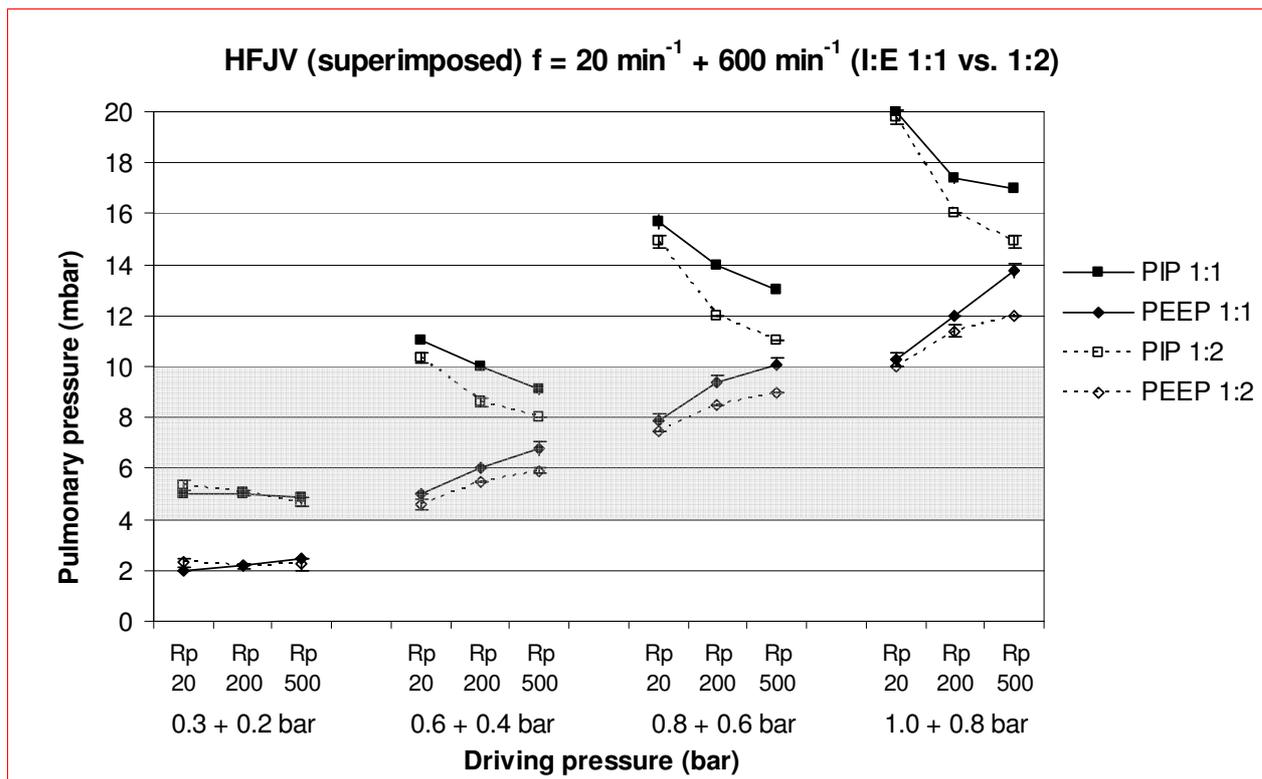


Fig. 6: Pulmonary pressures (mbar) during supraglottic superimposed HFJV (frequency: 20 br/min respectively 600 min^{-1} , I:E 1:2, 1:1 respectively) in various driving pressures and diameters of stenosis: peak inspiratory pressure (PIP) and positive end-expiratory pressure (PEEP). The marked area represents clinically adequate PEEP levels in ventilation of newborns and infants.

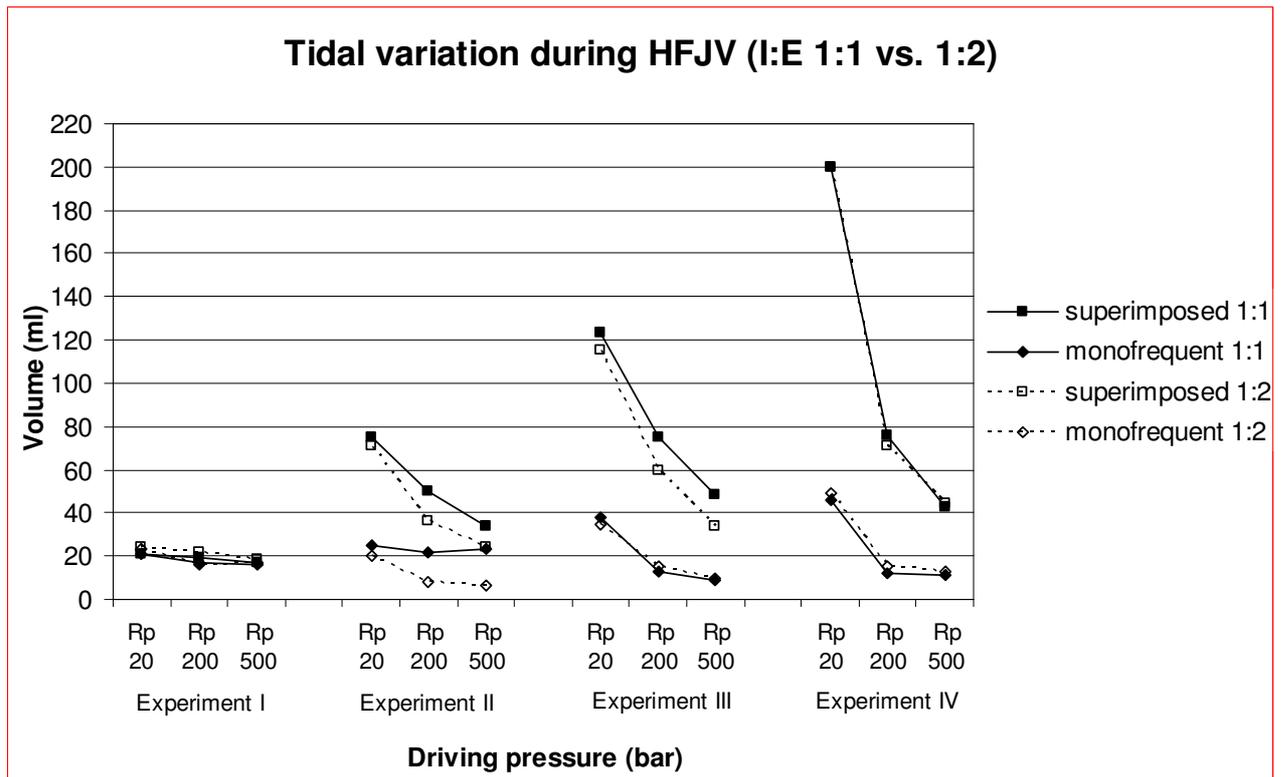


Fig. 7: Volume shifts during two conventional methods of HFJV in an infant trachea-lung model in various driving pressures and diameters of stenosis. Experiment I (superimposed HFJV: driving pressure 0.3 bar + 0.2 bar and monofrequent HFJV: driving pressure 0.3 bar). Experiment II (superimposed HFJV: driving pressure 0.6 bar + 0.4 bar and monofrequent HFJV: driving pressure 0.6 bar). Experiment III (superimposed HFJV: driving pressure 0.8 bar + 0.6 bar and monofrequent HFJV: driving pressure 0.8 bar). Experiment IV (superimposed HFJV: driving pressure 1.0 bar + 0.8 bar and in monofrequent HFJV: driving pressure 1.0 bar). Volume shifts are significantly higher during superimposed HFJV ($P < 0.05$) in Experiment II and Experiment III.

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6 **Experimental Model of Laryngotracheal Stenosis in Infants: Effects of Different**
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8 **High-frequency Jet Ventilation Patterns on Pulmonary Parameters**
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Running title: high-frequency jet ventilation, airway stenosis

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6 **Background:** Supraglottic high frequency jet ventilation (HFJV) in laryngotracheal surgery in
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8 infants with modified jet laryngoscopes offers the surgeon an unimpaired operating field. However,
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10 supraglottic HFJV is associated with the development of high airway pressures, inadvertent PEEP-
11
12 levels and barotrauma.
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15 **Methods:** We investigated the total lung volumes and tidal volume variations at peak inspiratory
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17 pressure levels (PIP) and at positive end-expiratory pressure levels (PEEP) along with the
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19 pulmonary pressures (PIP and PEEP) during two conventional methods of supraglottic high
20
21 frequency jet ventilation (HFJV) in an infant trachea-lung model without stenosis and with
22
23 different degrees of stenosis.
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26 **Results:** With augmentation of the driving pressure in the experiment without stenosis, the total
27
28 lung volume (TLV) plus the pulmonary pressures increased. With **narrowing** of the stenosis TLV
29
30 reduced at PIP level and increased at PEEP level. Volume shifts were significantly higher during
31
32 superimposed HFJV compared to monofrequent HFJV at equivalent stenosis diameter ($P < 0.05$)
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34 except for the setting with 0.3 bar driving pressure ($P > 0.05$). The pulmonary PIP was in none of
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36 the test series higher than 20 mbar and the pulmonary PEEP did not exceed 14 mbar.
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41 **Conclusions:** The results from our experimental model support the safe and effective clinical use
42
43 of supraglottic HFJV in infants with tracheal stenosis. Moderate driving pressures provide
44
45 acceptable pulmonary pressures in normal compliant lungs.
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55 **Keywords:** barotrauma, high frequency jet ventilation, infants, laryngotracheal stenosis
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Introduction:

Airway management and ventilation in infants with laryngotracheal stenosis is a big challenge because of the smallness of the airways. In addition to the anatomical and pathological particularities, the anaesthesiologist must be familiar with the specific features of the respiratory physiology and ventilation of infants. In our clinical routine we prefer total intravenous anaesthesia (TIVA), propofol supplemented with remifentanyl, in all cases with a partial or complete open anaesthesia system to guarantee a stable level of anaesthesia during the whole procedure and to avoid gas contamination for the operating team. ECG, heart rate, blood pressure and oxygen saturation is our standard monitoring. In addition the anaesthetist should carefully monitor the children clinically by auscultation the lungs and watching the chest movements. With high frequency jet ventilation (HFJV) oxygenation and ventilation during endoscopic surgery of the upper respiratory tract can be achieved. HFJV is in many cases the precondition for endoscopic treatment without tracheotomy, especially in LASER surgery. HFJV may be applied from a supraglottic position above the airway stenosis^{1, 2}; subglottic (infraglottic), using a catheter passed through the stenosis³ or transtracheal via a Ravussin cannula⁴. Due to the anatomical narrowness of the airways in infants and neonates even a cannula with 2 – 3 mm in diameter can impair the small surgical field during subglottic jet ventilation via transglottal (translaryngeal) cannulas. This fact can make endoscopic surgery impossible. Transtracheal jet ventilation via a Ravussin cannula is an invasive technique. In neonates and small infants the transcutaneous puncture of the cricothyroid membrane may be difficult and displacement of the cannula with cervical emphysema, pneumomediastinum and pneumothorax may occur. Supraglottic, prestenotic HFJV via modified Kleinsasser laryngoscope (Fig. 1) with integrated jet nozzels is a minimal-invasive ventilation technique and convenient for ventilation and oxygenation during endolaryngotracheal surgery in infants and neonates^{5, 6, 7}.

Fig. 1

In previous studies with adult trachea lung models, distal airway pressures, minute volumes and air entrainment were higher during ventilation above the stenosis compared to poststenotic HFJV^{8,9}. Thus supraglottic HFJV is associated with the development of inadvertent PEEP-levels and barotrauma.

The aim of this study was to assess the total lung volumes and tidal volume variations at peak inspiratory pressure (PIP) and at positive end-expiratory pressure level (PEEP), as well as the intrapulmonary pressures (PIP and PEEP) during two conventional methods of supraglottic HFJV in an infant trachea-lung model.

Material and Methods:

An artificial Infant Trachea (ID 4 mm) [Metron 5601i, Michigan Instruments Inc, US] connected with an Infant Test Lung (artificial Infant Trachea and Infant Test Lung are commercialised test systems for the respiratory care industry by ensuring patient safety through simulation of actual human lungs. Both are classified as a Class III Medical Device by the Food and Drug Administration), Compliance 0.01 L/cmH₂O (Metron 5601i, Michigan Instruments Inc, US) was ventilated with a TwinStream Jet Ventilator (C.Reiner, Vienna, A) via a Jet Laryngoscope for children (LAR SN 111, C. Reiner, Vienna, A). The jet nozzles are integrated in the wall of the laryngoscope, therefore no deviation or dislocation of the jet is possible. Lung volumes and intrapulmonary pressures were measured without airway stenosis and in the presence of airway stenosis. To simulate varying degrees of laryngotracheal stenosis as realistic as possible a Pneuflo® resistor (Rp) [Michigan Instruments Inc, US] was attached.

The narrowing in the artificial resistors is central (i.e. a concentric stenosis) like a pinhole.

Rp 200 [internal diameter (ID) 1.85 mm] equates an airway resistance of 200 cmH₂O/L/sec and Rp 500 (ID 1.3 mm) equates an airway resistance of 500 cmH₂O/L/sec. Rp 20 (without stenosis) equates an airway resistance of 20 cmH₂O/L/sec, which is the physiological resistance

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3 in infants with a body weight of ~ 10 kg. The drawing of the experimental infant trachea-lung-
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5 model is presented in fig. 2.
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8 Fig. 2
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10 Ventilator settings in all experiments were like the settings used in the daily routine for HFJV
11 in our department. The two sets of experiments were performed using the same lung-trachea
12 model. We applied the various conditions (driving pressure, I:E ratio) for monofrequent high
13 frequency jet ventilation and in the following for superimposed high frequency jet ventilation.
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19 The ventilator setting for superimposed high frequency jet ventilation (SHFJV) was: frequency
20 20 breaths/min combined with 600 min⁻¹, I:E 1:2 and followed by 1:1. The ventilation was
21 performed with a driving pressure 0.3 bar in the low frequency part and 0.2 bar in the high
22 frequency part of jet ventilation, followed by driving pressures in the low/high conditions of 0.6
23 + 0.4, 0.8 + 0.6 and 1.0 + 0.8 bar.
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31 Ventilator settings for the monofrequent, high frequency jet ventilation were: frequency
32 200 min⁻¹, I:E 1:2 followed by 1:1. The driving pressure for ventilation was 0.3, 0.6, 0.8 and
33 1.0 bar.
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38 The recording of the data at steady state were repeated five times for all diameters of the
39 airway. The test lung houses an electronic interface module. The module converts pressure
40 signals from the test lung and airways into digital data. For recording and calculation of the
41 data we used the PneuView® Software (Michigan Instruments Inc, US) on a personal
42 computer.
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50 Microsoft Excel 2003 and SPSS 17.0 for Windows (SPSS Inc., Chicago, IL, U.S.A), were used
51 to aid data analysis and illustration. The Wilcoxon signed rank test was applied and P < 0.05
52 was considered statistically significant. Data were presented as mean ± SD if not otherwise
53 specified.
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Results:*Effect of supraglottic monofrequent HFJV in various driving pressures and stenosis*

With augmentation of the driving pressure in the setting without stenosis (Rp 20), the lung volume as well as the pulmonary pressures increased. In the experiment with 1.0 bar driving pressure PIP increased up to a maximum of 14 ± 0 mbar and PEEP up to a maximum of 12 ± 0 mbar. With decreasing diameter of the stenosis (Rp 200 = 1.85 mm ID and Rp 500 = 1.3 mm ID), PEEP as well as total lung volume (TLV) at PEEP-level increased, while peak inspiratory pressure (PIP) and TLV at PIP-level decreased. During ventilation with I:E ratio of 1:2 the PIP and PEEP values were lower in comparison to I:E ratio 1:1 (Fig. 3; Fig. 4)

Fig. 3; Fig. 4

Effect of supraglottic, superimposed HFJV with various driving pressures and stenosis

Superimposed HFJV is generated by overlaying a low-frequency jet stream with a high-frequency jet stream. With augmentation of the driving pressure in the experiment without stenosis (Rp 20), the total lung volume as well as the pulmonary pressures increased (Fig. 5). In the experiment with 1.0 + 0,8 bar driving pressure PIP increased up to a maximum of 20 ± 0 mbar and PEEP up to a maximum of 10.5 ± 0 mbar. With decreasing diameter of the stenosis (Rp 200 = 1.85 mm ID and Rp 500 = 1.3 mm ID) total lung volume at PIP level decreased and the total lung volume at PEEP level increased (Fig. 5). During ventilation with I:E ratio of 1:2 the PIP and PEEP values were lower in comparison to I:E ratio 1:1 (Fig. 6).

Fig. 5; Fig. 6

Effect of I:E ratio in supraglottic HFJV with various driving pressures and stenosis

For both, monofrequent HFJV (Fig. 4) and superimposed HFJV (Fig. 6), it was registered that without stenosis there was no significant difference in pulmonary pressures and tidal variation between I:E of 1:2 and 1:1. In presence of airway stenosis pulmonary pressures, especially PEEP, increased at I:E 1:1, while tidal variations hardly changed. This effect was more distinct in monofrequent HFJV.

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3 Tidal variations during superimposed supraglottic HFJV are significantly higher ($P < 0.05$) in
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5 Experiment II and Experiment III, than during monofrequent supraglottic HFJV. That two
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7 settings are identical with the ventilations settings generally used in our clinical routine (Fig. 7).
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10 Fig. 7
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15 Discussion: 16 17

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19 In this infant trachea lung model we tried to simulate the specific features of the respiratory
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21 physiology and ventilation of infants in the presence of airway stenosis to analyse our clinical
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23 experiences in supraglottic HFJV in neonates, infants and children. We use this technique in
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25 clinical practice since 13 years without severe complications. In all cases we have to share the
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27 airway with surgeon.
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30 The characteristics of the respiratory system of infants in contrast to adults are the unstable
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32 functional residual capacity (FRC), a lower compliance (C) and a higher resistance (R).
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34 Therefore a positive end-expiratory pressure (PEEP) in artificial ventilation of newborns and
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36 infants^{10, 11} is preferable and its occurrence in an acceptable level during supraglottic HFJV
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38 might be advantageous. Varied techniques of airway management and anaesthesia during
39
40 endolaryngotracheal surgery in children are in clinical practice. Each of these techniques offers
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42 advantages and disadvantages¹². Conventional positive pressure ventilation via tracheal tube
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44 may not be practicable due to the stenosis itself or to the surgical request for an unhindered
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46 operating field. Spontaneous ventilation or apnoeic anaesthesia with intermittent ventilation and
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48 oxygenation is often used in pediatric ENT surgery^{13, 14}. Children may develop a loss of about
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50 45 % of their functional residual air capacity (FRC) during general anaesthesia and owing to
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52 inadequate ventilation, hypoxia may occur in a matter of seconds^{10, 11}. Thus the
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54 anaesthesiologist is obliged to switch to alternative ventilation and oxygenation techniques.
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3 Supraglottic HFJV ensures oxygenation and ventilation and offers the surgeon an unimpaired
4 operating field. According to our experimental results, supraglottic HFJV seems to be able to
5 ensure adequate ventilation and provide acceptable PEEP-levels ^{10, 11}. The efficacy and safety
6 for ventilation and oxygenation during this specific kind of surgery is not clearly established
7 and guidelines for the use of such techniques would be welcome ¹⁵. In adult lung model
8 suprastenotic HFJV is associated with higher airway pressures and with higher risk for
9 barotrauma as compared to infrastenotic HFJV in the presence of airway stenosis ^{8,9}.

10 Because of the anatomical and physiological features of the respiratory system of infants, these
11 findings concerning adult lung-trachea models can not be transferred to children. With respect
12 to the higher resistance and lower compliance, it might be assumed that this effect is even
13 greater in infant`s lungs. Numerous large, published series have reported their experiences with
14 supraglottic HFJV without severe complications such as barotrauma ^{5, 6, 7, 16, 17, 18}.

15 Several authors of previous studies have investigated the airway pressures. In our experiment
16 we measured the pulmonary total volume in an infant test lung at PIP-level and at PEEP-level,
17 which probably is an indicator for impending barotrauma. We recorded the pulmonary
18 pressures at PIP-level and at PEEP-level during ventilation of the infant test lung with two
19 conventional methods of HFJV.

20 A previous report by Ihra et al¹⁹ demonstrated in an adult trachea-lung model, that the distance
21 between the jet nozzle and the airway stenosis influences airway pressure, so that airway
22 pressures decrease with increasing distance to the stenosis.

23 The moderate pulmonary pressures we measured in both forms of HFJV may be due to the use
24 of the modified Kleinsasser laryngoscope, in which the distance between the plane of exit of the
25 jet stream and the tip of the laryngoscope is constant and depending upon the size of
26 laryngoscope in children, ranging from 7.7 cm, respectively 9.7 cm. This fact may prevent high
27 pulmonary pressures related to the tightness of the stenosis and different driving pressures.

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3 Jet cannulas introduced into the laryngoscope hold the risk of dislocation and anomalies in
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5 airway pressures with possibly consecutive high pulmonary pressures.
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8 As expected volume shifts during superimposed HFJV were higher than during monofrequent
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10 HFJV. This correlates with our clinical observations of an adequate CO₂-elimination during
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12 superimposed HFJV ⁷.
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15 We assume that another factor for the reasonable pulmonary pressures may be the application
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17 of comparatively low driving pressures, as we use in the daily routine. With the ventilator
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19 settings used in our study and in both conventional methods of HFJV, no clinically inadequate
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21 pressure levels occurred in any experiment (fig.4, fig. 6).
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24 Furthermore our results suggest that an I:E ratio of 1:2 can be recommended for HFJV applied
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26 to a constricted airway. I:E of 1:1 is associated with higher pulmonary pressures and does not
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28 lead to augmented ventilation. The abbreviated expiration time at 1:1 ratio may induce
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30 aggravated air trapping.
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33 Our findings also show that augmentation of the driving pressure is inappropriate to increase
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35 ventilation in presence of airway stenosis. Increasing driving pressures only lead to higher
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37 pulmonary pressures while tidal volumes do not change significantly. This suggests that the risk
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39 for barotrauma may escalate, although ventilation cannot be improved. Hence the application of
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41 moderate driving pressures seems to be safe concerning pulmonary pressures and provides
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43 adequate ventilation.
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47 One shortcoming of supraglottic HFJV in the clinical routine is the fact that airway pressures
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49 and endtidal CO₂ cannot be measured continuously, because of the open ventilation system.
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52 Another problem inherent in an in vitro study is the [direct translation](#) to clinical practice. The
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54 setting of our test lung corresponds to the physiological condition of children about up to 10 kg
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56 of body weight. Larger children may present different respiratory parameters such as
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58 compliance or resistance and therefore differing pressure and volume data may occur.
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3 The stenosis (resistor) applied to the model shows the form of a blind, which can be seen in the
4 clinical practice in subglottic stenosis after long term intubation. Airway stenosis of a length of
5 more than a few millimetres or even centimetres could not be analysed and may change our
6 results. Furthermore the model stenosis used, is composed of inflexible material in contrast to
7 in-vivo airway stenosis which can consist of soft tissue. The effect of these phenomena,
8 concerning intrapulmonary volume and pressure remains unconsidered in this study. Based on
9 our clinical experiences, we can not say, that this technique is safe in distal tracheal stenosis
10 also tidal volumes and driving pressures may be inadequate in poorly compliant lungs which
11 was not reviewed in our studies.
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24 Further clinical and experimental studies are needed to take a closer look at the airway
25 management and ventilation during these specific surgical procedures in infants.
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29 On the basis of the data from this study, we conclude that supraglottic HFJV in infants with
30 modified jet laryngoscopes is a minimally invasive and safe ventilation technique, it offers an
31 unimpaired operating field for the surgeon especially in LASER surgery and this method
32 ensures sufficient ventilation with adequate PEEP via optimally adjusted jet mechanism.
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44 We are grateful to Mr. D. Lirsch (C. Reiner, Vienna) for his support with the laboratory work.
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For Peer Review