



Peak airway pressure is lower during pressure-controlled than during manual facemask ventilation for induction of anesthesia in pediatric patients—a randomized, clinical crossover trial

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Abstract

Purpose Facemask ventilation during the induction of general anesthesia in paediatric patients remains a challenge as it may result in hypoxic conditions and gastric insufflation with subsequent regurgitation and aspiration. So far, it is unclear if pressure-controlled or manual facemask ventilation is preferable in children. We hypothesized that pressure-controlled ventilation in apnoeic children results in lower peak airway pressure and flow rates compared to manual ventilation at comparable respiratory rates and tidal volumes.

Methods Sixty-two lung-healthy children undergoing scheduled ear-nose-throat surgery were included in the study. After the induction of anesthesia, the patient's lungs were consecutively ventilated via a facemask in either manual or pressure-controlled mode, in randomized order. The primary outcome measure was peak airway pressure. Secondary outcome measures included positive end-expiratory pressure, airway compliance, tidal volume and airway flow.

Results Data of 52 patients could be analyzed. Pressure-controlled ventilation resulted in a lower mean and peak inspiratory pressure (both $p < 0.001$), airway pressure amplitude ($p = 0.01$) and inspiratory peak flow rate ($p = 0.005$) compared to manual ventilation. The ratio of inspiration to expiration time was lower in pressure-controlled ventilation compared to manual ventilation ($p < 0.001$).

Conclusion Pressure-controlled facemask ventilation during induction of anesthesia in pediatric patients results in lower airway pressure, and lower flow rates compared to manual ventilation, at comparable tidal and minute volumes.

Keywords Pressure support ventilation · Pediatric anesthesia · Gastric regurgitation · Patient safety

Introduction

It is considered standard practise for the anesthetists to perform manual facemask ventilation during the induction of anesthesia in pediatric patients until endotracheal intubation is carried out. Therefore, the patient's oxygenation relies on operator dependent factors such as the manually applied airway pressure, gas-flow, and respiratory rate [1]. The combination of manual pressure application using a reservoir bag and arbitrary respiratory rate makes it difficult to control

tidal volume and minute volume, peak flow rate and peak pressure. Under these conditions, the monitoring of adequate ventilation by only the analysis of end-expiratory carbon-dioxide partial pressure appears imprecise.

Von Goedecke and co-workers analyzed the effects of manual facemask ventilation and pressure-controlled facemask ventilation in adults with unprotected airways, and found that pressure-controlled facemask ventilation resulted in lower peak airway pressures and flow rates [2]. Ensuring more safety to the unprotected airway, it has been suggested that pressure-controlled facemask ventilation may be superior to manual facemask ventilation [3]. However, data on respiratory variables during pressure-controlled facemask ventilation and manual facemask ventilation in children are missing. Therefore, we wanted to compare respiratory airway measures during pressure-controlled facemask ventilation and manual facemask ventilation in apnoeic children during induction of anesthesia.

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We hypothesized, that pressure-controlled facemask ventilation would result in lower inspiratory peak airway pressures and flow rates in pediatric patients compared to manual facemask ventilation.

Materials and methods

The present study was approved by the local ethics committee of the University Medical Center Freiburg (EK 140/12), and registered at the clinical trial register (DRKS Study Number: 00003973; UTN U1111-1130-7818) before enrollment of the first patient. Seventy-six pediatric patients presenting at the Department of Ear-Nose-Throat Surgery of the University Medical Center Freiburg and scheduled for elective surgery (Status I–III according to the classification of the American Society of Anesthesiologists (ASA), ranging from 1 to 12 years) were screened for eligibility (Fig. 1). After obtaining informed written consent of both parents or a legal guardian, children were enrolled in this study. The primary endpoint variable was peak airway pressure. Secondary endpoint measures included positive end expiratory pressure (PEEP), peak flow rate, gastric insufflation, respiratory system compliance, tidal volume and

minute ventilation as well as the quotient of inspiration-to-expiration time (I:E-ratio).

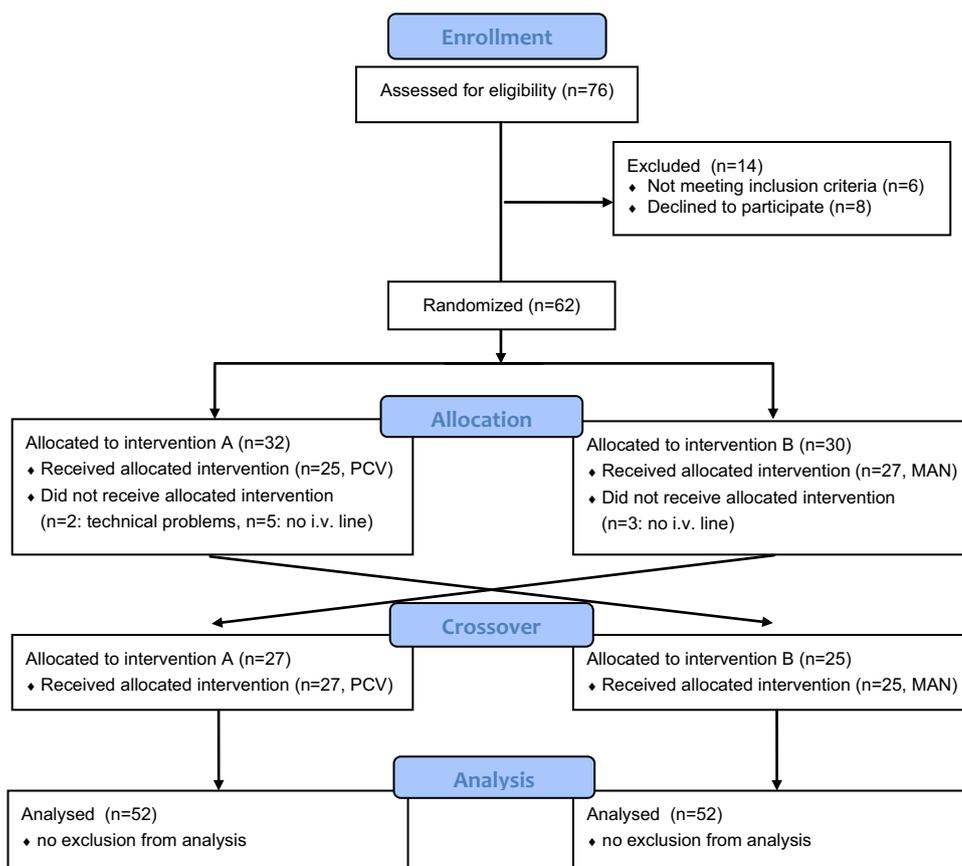
Exclusion criteria were ASA status IV or above, age below 1 year or above 12 years, body mass index $> 30 \text{ kg/m}^2$, increased risk of aspiration (defined as known gastro-oesophageal reflux or fasted $< 2 \text{ h}$ for clear fluids or $< 6 \text{ h}$ for solids), respiratory infection, refusal of data acquisition by either the patient, a parent or a legal guardian or problems regarding explanations in the German language with the parents or legal guardian.

After the induction of anesthesia, patients were randomly allocated to one of the treatment groups. The randomization sequence was computer-generated before patient enrollment (<http://www.random.org>). Depending on the respective group, the patients either received first manual facemask ventilation, then pressure-controlled facemask ventilation or the other way round to ensure the randomized cross over design. The first ventilation mode was applied for 60 s, followed by ventilation in the respective other mode for 60 further seconds.

Anesthesia induction

Midazolam was given as an oral premedication at least 1 h prior to induction of anesthesia [0.2 mg/kg bodyweight

Fig. 1 CONSORT flow chart



(BW), max. 3.75 mg]. All patients were positioned in a standardized head and neck position, that was supine position with the head on a soft pillow on the operating table. After the routine monitoring was implemented (electrocardiogram, oxygen saturation- and non-invasive blood pressure measurement) additional bispectral index (BIS) electrodes were placed on the patient's head to ensure deep anesthesia before starting the measurements. An intravenous catheter was inserted and induction of anesthesia was performed following a standard protocol. The size of the pediatric facemask (Laerdal Infant Mask, Size #2 or #3, Laerdal Medical GmbH, Puchheim, Germany) was chosen to fit the individual requirements. If necessary, the head was exposed in a more backward position with the chin lifted to open the airways and ease facemask ventilation. Patients breathed pure oxygen via the sealed facemask at a fresh gas flow of 4 L/min generated by the ventilator (Fabius Tiro, Draeger, Luebeck, Germany) with an open airway-pressure-limit valve. When the expired oxygen fraction reached 0.85 or above, pre-oxygenation was considered complete and anesthesia was induced by administration of 0.5 $\mu\text{g}/\text{kg}/\text{min}$ remifentanyl (Glaxo Smith Kline, Germany) within 60 s (afterwards reduced to 0.15 $\mu\text{g}/\text{kg}/\text{min}$) and 3–5 mg/kg propofol (Fresenius Kabi, Germany) over a time period of 30 s (afterwards 120 $\mu\text{g}/\text{kg}/\text{min}$). Initial ventilation was assessed by gentle manual ventilation while bi-lateral chest expansion as well as capnography were observed over a period of one minute. BIS was expected to have reached 40 or less by this time, otherwise additional propofol (0.5 mg/kg) was given until BIS reached 40; BIS was maintained at this level throughout the procedure [4]. From now on, head and neck of the patient were kept in the current position throughout the measurement period for the proper comparison of manual facemask ventilation and pressure-controlled facemask ventilation.

Data of BIS, heart-rate, oxygen saturation and end-tidal carbon dioxide pressure were recorded continuously, while non-invasive blood pressure was recorded in 1 min intervals throughout the time of the study.

The following procedures were performed by 12 different anesthetists who had at least 4 years experience under supervision of the consultant in charge. The attending anesthetists performed both ventilation modes with holding the facemask with only the left hand, keeping the right hand at the circle system bag (in case of manual facemask ventilation) or not in use (in case of pressure-controlled facemask ventilation). During all measurements he or she was not able to see the patient monitor or the anesthesia machine monitor.

The respiratory variables were measured using a respiratory profile monitor (CO₂SMO plus, Novamatrix Medical Systems Inc., Wallingford, Connecticut, USA) with a pediatric combined flow rate and CO₂ sensor (Respironics California Inc., Carlsbad, CA, USA). The sensor's cuvette was connected to the ventilation mask

with the CO₂ sampling port positioned proximal to the patient. The respiratory monitor was connected to a laptop for recording the respiratory data, using the "aplus" software package of Novamatrix. The average peak airway pressure across all applied breaths within a measurement and the maximal inspiratory peak pressure within a measurement were determined. Furthermore, the average and maximal airway pressure amplitudes, i.e. the difference of peak inspiratory pressure and positive end-expiratory pressure (PEEP, $\Delta\text{Paw} = \text{PIP} - \text{PEEP}$), were calculated as measures for the peak pressure generated by the respective ventilation mode.

Settings for pressure-controlled facemask ventilation were as follows: respiratory rate was set with regard to respective patient's age in agreement with the attending anesthetists ($f = 14$ to 20/min), the pressure limit was set to achieve a tidal volume of 7 ml/kg, PEEP was set at 0 cm H₂O, and I:E ratio was set at 1:1. For manual facemask ventilation the airway-pressure-limit valve was set to release pressures > 20 cm H₂O, and fresh gas flow was set at 0.5 L/min to compensate for facemask leakage. To achieve the targeted respiratory rate (identical to pressure-controlled facemask ventilation for each individual patient) an electronically synchronized clock-pulse generator indicated time intervals of inspiration and expiration. The anesthetist was asked to perform mask ventilation in the usual way, i.e. watching chest movement and capnography as signs for adequate ventilation. After setting of the respective ventilation condition, system equilibration was allowed for one minute, and subsequently data were recorded for 60 s, respectively.

After acquisition of the data, the patients tracheas were intubated and the surgical procedures were conducted as intended.

Analysis of the data was performed in a blinded manner by our statistician who was not part of the OR team; the staff anesthetist on-site could not be blinded for his action for obvious reasons.

Statistics

An a-priori power analysis provided by the Department of Medical Biometrics and Informatics indicated that a sample size of 26 children per group would be adequate ($\alpha = 0.1$ with two-sided hypothesis, $\beta = 0.9$, effect size 0.5, assumed standard deviation 2 cm H₂O) regarding peak airway pressure. Data are presented as mean \pm standard deviation if normally distributed (demographics and values of vital signs) or median with 95% confidence interval unless noted otherwise. Data were analyzed using two-way ANOVA. Potential correlations between inspiratory airway pressure and inspiratory airway resistance were analyzed via linear regression analysis.

A p value < 0.05 was considered to indicate a significant difference. The analyses were performed using the SigmaStat 11.0 software (Systat, Erkrath, Germany).

Results

After screening 76 children (Fig. 1), 14 patients were excluded prior to the beginning of the study, because they did not meet the inclusion criteria ($n = 6$), declined to participate ($n = 8$). Thus, 62 children were included in the study. Ten patients were excluded either due to technical problems while obtaining respiratory data ($n = 2$) or because the intravenous line could not be placed initially and induction of anesthesia with volatile anesthetics was necessary ($n = 8$). In total, data from 52 children could be analyzed. The numbers of individual surgical procedures are presented in Table 1.

Patients' characteristics and values of vital signs did not differ between both ventilation conditions (Table 2). Further, respiratory rate, tidal volume, minute volume and PEEP did not differ between both ventilation conditions (Table 3). The average inspiratory peak pressure and peak flow rate were

significantly lower during pressure-controlled facemask ventilation compared to manual facemask ventilation (both $p < 0.01$). The maximal inspiratory peak pressure within a ventilation sequence manual facemask ventilation exceeded that during pressure-controlled facemask ventilation significantly by 42% ($p < 0.001$). ΔP_{aw} was significantly lower during pressure-controlled facemask ventilation compared to manual facemask ventilation ($p = 0.01$). Peak expiratory flow was significantly higher during pressure-controlled facemask ventilation compared to manual facemask ventilation ($p = 0.04$). The I:E ratio was significantly lower during pressure-controlled facemask ventilation compared to manual facemask ventilation ($p < 0.001$).

Inspiratory airway pressure and inspiratory airway resistance were only weakly, however, significantly correlated with each other during pressure-controlled facemask ventilation ($r^2 = 0.21$, $p < 0.001$) and manual facemask ventilation ($r^2 = 0.36$, $p < 0.001$, Fig. 1).

No stomach insufflation was observed during the measurements and postoperatively, no incidence of aspiration or PONV and no other signs of any harm related to our investigation (i.e. sore throat were detected in any patient directly after the ventilation maneuvers of within following 2 days) was observed in either group. No chest wall rigidity or glottic closure was observed in any children at any timepoint during the measurements.

Discussion

The main findings of this clinical trial can be summarized as follows: pressure-controlled facemask ventilation during induction of anesthesia reduced average and maximal inspiratory peak pressure as well as airway pressure amplitude and

Table 1 Surgical procedures of patients

Surgical procedure	n
Cochlear implant	22
Adenectomy	5
Tympanostomy tube	9
Tonsillectomy	6
Lateral collar zyst	3
Cholesteatom	2
Panendoscopy	3
Tympanoplastic	2
Total number	52

Table 2 Patient characteristics and vital parameters of groups with first intervention manual facemask ventilation and first intervention pressure-controlled facemask ventilation

	First manual	First pressure-controlled
Number of patients (n)	27	25
Age (years; mean \pm standard deviation, range)	5 \pm 2.4 (1–12)	4 \pm 3.4 (2–10)
Sex (female/male)	12/15	12/13
Weight (kg; mean \pm standard deviation)	19 \pm 6	20 \pm 6
Height (cm; mean \pm standard deviation)	112 \pm 17	114 \pm 13
ASA (I/II/III)	9/12/5	8/13/5
Bispectral index (arbitrary)	26 \pm 13	28 \pm 11
Heart rate (bpm)	75 \pm 10	78 \pm 12
Non invasive blood pressure (mm Hg), systolic	85 \pm 11	90 \pm 8
Non invasive blood pressure (mm Hg), diastolic	47 \pm 7	44 \pm 9
Oxygen saturation (%)	99 \pm 1	99 \pm 1
End-tidal carbon dioxide (mm Hg)	37 \pm 4	35 \pm 5

ASA = patient status according to the fitness classification of the American Society of Anesthesiologists. Data are given as mean \pm SD if not indicated otherwise

Table 3 Respiratory characteristics during manual and pressure-controlled facemask ventilation

Variable	Manual	Pressure-controlled	<i>p</i> value
Respiratory rate (breaths/min)	15 ± 1	15 ± 1	0.879
Inspiratory tidal volume (mL)	201 ± 69	226 ± 90	0.939
Expiratory tidal volume (mL)	136 ± 51	150 ± 55	0.450
Minute volume (L)	2.2 ± 0.75	2.1 ± 0.75	0.655
PEEP (cm H ₂ O)	4.2 ± 1.5	3.1 ± 0.7	<0.001
Average Peak inspiratory pressure (cm H ₂ O)	13.4 ± 2.9	10.2 ± 1.8	<0.001
Maximal Peak inspiratory pressure (cm H ₂ O)	17.3 ± 2.2	12.2 ± 1.5	<0.001
Airway pressure above PEEP (cm H ₂ O)	10.2 ± 2.5	9.1 ± 1.7	0.012
Peak inspiratory flow (L/min)	13.3 ± 3.3	11.7 ± 2.4	0.005
Peak expiratory flow (L/min)	9.7 ± 2.5	10.6 ± 2.1	0.041
Inspiratory time (s)	1.9 ± 0.6	2.0 ± 0.3	0.559
Ratio inspiration/expiration (I:E)	1.55 ± 0.46	1.03 ± 0.16	<0.001
Dynamic compliance (L/cm H ₂ O)	39.4 ± 15.3	33.8 ± 18.3	0.507
Inspiratory Airway resistance (cm H ₂ O/L/s)	31.8 ± 19.5	34.2 ± 21.9	0.317
Expiratory Airway resistance (cm H ₂ O/L/s)	32.5 ± 19.8	35.5 ± 22.1	0.321
Stomach insufflation (<i>n</i>)	0	0	–

Data are mean ± standard deviation

PEEP positive end-expiratory pressure

inspiratory peak flow rate compared to manual facemask ventilation.

Induction of general anesthesia in pediatric patients remains a challenge regarding the unprotected airway management [5–7]. Especially, potential patient movement, airway obstruction, coughing or hick-ups during the induction of anesthesia impede facemask ventilation [8, 9]. Reasoned by the mandatory facemask ventilation, patients face an increased risk of regurgitation and aspiration during anesthesia induction, until neuromuscular blocking allows to protect the airways by tracheal intubation [10]. This risk increases with increasing ventilation pressure [11–13]. In this respect, our results demonstrate advantages of pressure-controlled facemask ventilation over manual facemask ventilation, as better controlled and consequently lower peak pressures and flow rates were generated. This is in agreement with studies in adults [11].

It is common practice to limit peak pressure at 20 cm H₂O, as the lower oesophageal sphincter may show insufficiency at higher pressure [14]. Lagarde and coworkers demonstrated impressively, that gastric insufflation in children depends on age and on the applied inspiratory pressure [11]. The risk of gastric insufflation with consecutive aspiration of gastric contents in children is higher compared to adult patients and varies mainly with the age and the current condition [12, 13]. While a moderate peak inspiratory pressure (< 15 cm H₂O) seems to be safe for most children weighing more than 20 kg, smaller children are at increased risk (threshold < 10 cm H₂O) [11]. In the present study, we demonstrated that the average peak pressure was higher during manual facemask ventilation than during pressure-controlled

facemask ventilation (13 versus 10 cm H₂O). Regarding the gastric opening pressure this means, however, that application of pressure-controlled facemask ventilation increases the ‘safety range’ by 20–30% compared to manual facemask ventilation. Moreover, the manual pressure generation was associated with a noticeable variability, as the difference between the observed maximal and average peak pressure (17 versus 13 cm H₂O) demonstrates; thus the risk of exceeding gastric opening pressure in individual manual breaths is much higher than the average values might suggest.

Especially in difficult airway situations, facemask ventilation may be the ultimate instrument for avoiding hypoxemia. Comparing mechanical versus manual facemask ventilation von Goedecke concluded that mechanical facemask ventilation is safer in terms of lower applied inspiratory peak pressure [2]. In contrast to their study, we ensured a constant respiratory rate by giving audio signals to avoid influences of the anesthetists’ personal rhythm on the pressure course. Thereby, we achieved that manually applied inspiratory and expiratory tidal volumes matched the mechanically applied ones.

In our study, a 20% reduction in peak inspiratory flow rate was found during pressure-controlled ventilation. Although airway leakage limits the precision of expiratory volume analysis, this difference can be directly attributed to the variable pattern of inspiratory flow caused by the manual ventilation. Of note, inspiratory and expiratory peak flow differed significantly between ventilation conditions. While inspiratory flow was higher, expiratory flow was lower during manual facemask ventilation than during pressure-controlled facemask ventilation. This may be associated with both, a

more powerful, manual compression of the ventilation bag and the different resistance conditions resulting from of the, respectively, active expiration valves during both ventilation modes. This may also have caused the observed differences in I:E-ratio.

In context with the pressure generation it has to be noted that besides inspiratory flow, airway resistance is of course a determinant for airway pressure. However, based on the weak correlations between peak inspiratory pressure and inspiratory resistance during pressure-controlled facemask ventilation and manual facemask ventilation we conclude that airway resistance had only minor impact on our results.

During pressure-controlled facemask ventilation the PEEP, generated by fresh gas flow, was significantly lower compared to manual facemask ventilation. It is questionable, whether this fact may be interpreted as beneficial or disadvantageous in the light of airway collapse and atelectasis. A PEEP level of 3–5 cm H₂O is generally recommended [15], however, Humphreys et al. demonstrated that PEEP levels during the induction period of anesthesia have only moderate significance [16].

Compared to the study of von Goedecke [2] the airway pressure amplitudes calculated as the difference between peak inspiratory pressure and PEEP ($\Delta P_{aw} = PIP - PEEP$) were significantly lower in our study in pediatric patients. We attribute this to the lower applied peak inspiratory pressure. As we observed similar sufficient gas exchange during both ventilation modes we feel justified to assume that an adequate ventilation in pediatric patients might be achieved at lower peak pressures.

Beside the lower variability of an automated ventilation mode, allowing accurate tidal volumes and steady low pressures, the eliminated task of manual bag compression allows the anesthetist to focus on the pediatric patient and (if needed) to use both hands to hold the facemask in an adequate position. This may be of particular relevance, when a difficult airway situation becomes evident. Taken together, we feel that pressure-controlled facemask ventilation may be preferable compared to manual facemask ventilation in pediatric patients.

Limitations of the study

A limitation of our study is that we did not determine gastric air insufflation. The study's primary end points focussed on the respiratory variables during the tested ventilation conditions and, e.g. auscultation of the epigastric area or observation of gastric insufflation with ultrasound were not part of the protocol.

Only children with ASA status I–III scheduled for elective surgery were enrolled. Therefore, generalizability of the results to children with ASA IV or above may be questionable.

Although oxygen saturation did not differ between both ventilation conditions in our study, it would be interesting to analyse arterial partial oxygen pressure. However, placement of an arterial line for the purpose of this study would not have been justifiable for ethical reasons.

Only children > 1 year were included in the study and our patients showed a large age range. In infants gastric insufflation of air may have more relevant consequences. However, we did not observe age related differences in any result.

Conclusion

Our data demonstrate, that the mechanically applied pressure-controlled facemask ventilation during the anesthesia induction in pediatric patients reduces inspiratory peak pressure and flow rate compared to manual facemask ventilation.

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Compliance with ethical standards

Conflict of interest None of the authors has any conflict of interest.

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