Respiratory Physiology & Neurobiology 234 (2016) 9–13

Contents lists available at ScienceDirect

Respiratory Physiology & Neurobiology

journal homepage: www.elsevier.com/locate/resphysiol

Intratidal recruitment/derecruitment persists at low and moderate positive end-expiratory pressure in paediatric patients

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ARTICLE INFO

Article history:
Received 18 May 2016
Received in revised form 4 August 2016
Accepted 23 August 2016
Available online 29 August 2016

Keywords:
Mechanical ventilation
Lung compliance
Children
Functional residual capacity
Protective ventilation
Compliance–volume curve
Respiratory system mechanics

ABSTRACT

In paediatric patients positive end-expiratory pressure (PEEP) is traditionally set lower than in adults. We investigated whether moderately higher PEEP improves respiratory mechanics and regional ventilation. Therefore, 40 children were mechanically ventilated with PEEP 2 and 5 cmH_2O. Volume-dependent compliance profiles were analysed as a measure of intratidal recruitment/derecruitment. Regional ventilation was assessed using electrical impedance tomography.

Mean compliance was 17.9 ± 9.9 mL cmH_2O^{-1} (PEEP 2 cmH_2O), and 19.0 ± 10.9 mL cmH_2O^{-1} (PEEP 5 cmH_2O, $p < 0.001$). Strong intratidal recruitment/derecruitment occurred in 40% of children at PEEP 2 cmH_2O, and 36% at PEEP 5 cmH_2O. Children showing strong recruitment/derecruitment were 33 (PEEP 2 cmH_20) and 20 (PEEP 5 cmH_20) months younger than children showing moderate recruitment/derecruitment. A higher PEEP improved peripheral ventilation.

In conclusion, mechanically ventilated paediatric patients undergo intratidal recruitment/derecruitment which occurs more prominently in younger than in older children. A PEEP of 5 cmH_2O does not fully prevent intratidal recruitment/derecruitment but homogenizes regional ventilation in comparison to 2 cmH_2O.

1. Introduction

General anaesthesia with mechanical ventilation leads to atelectasis formation due to airway collapse in children as well as in adults (Brismar et al., 1985; Kaditis et al., 2008; Tusman et al., 2003). Studies in adults have shown that intraoperative lung-protective ventilation can reduce the rate of postoperative pulmonary complications (Futier et al., 2013; Severgnini et al., 2013). In a recent study we have shown that a higher positive end-expiratory pressure (PEEP) was associated with an improved intratidal compliance (Wirth et al., 2015). However, there are no studies that investigated the intratidal derecruitment during general anaesthesia in paediatric patients. Regarding lung volume, the balance between functional residual capacity (FRC) and closing capacity, being the relative volume below which the smallest airways collapse, determines the recruitment situation of the lungs (Neumann and von Ungern-Sternberg, 2014). Children have a lower relative FRC compared to adults and the closing capacity exceeds the FRC especially in patients under the age of six years (Dobbinson et al., 1973; von Ungern-Sternberg et al., 2006). Additionally, induction of anaesthesia results in a noticeable drop of the FRC in paediatric patients (von Ungern-Sternberg et al., 2007a). This promotes quick and frequent formation of intraoperative atelectasis in the child and thus inhomogeneous ventilation of the lungs. The application of PEEP increases FRC and improves compliance of the respiratory system (C_{RS}). Using computed tomography, Serafini and colleagues (Serafini et al., 1999) have shown that atelectasis is thereby reduced. The current strategy of lung-protective ventilation involves the application of PEEP to prevent intratidal recruitment/derecruitment and low tidal volumes to minimize inspiratory airway pressure, which could contribute to ventilator-induced lung injury due to overdistension (Amato et al., 2015; Duggan and Kavanagh, 2005). There are no guidelines for PEEP settings in paediatric patients. Nevertheless, anaesthesiologists traditionally set PEEP to a lower level in paediatric patients than in adults, i.e. below 5 cmH_2O.

A PEEP of 2 cmH_2O which was suggested as lowest limit (Coté and Lerman, 2013) in paediatric patients. Therefore, we conducted the present study to investigate the effects of PEEP at 5 cmH_2O in

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http://dx.doi.org/10.1016/j.resp.2016.08.008
1569-9048/

comparison to PEEP 2 cmH_2O on the intratidal respiratory mechanics and regional ventilation in children under general anaesthesia. We hypothesized that respiratory mechanics in children would improve in terms of less intratidal recruitment/derecruitment and more homogeneous regional ventilation at a PEEP of 5 cmH_2O when compared to a PEEP of 2 cmH_2O. Therefore, we determined the respiratory system mechanics to identify the presence of intratidal recruitment/derecruitment or overdistension and assessed regional ventilation using electrical impedance tomography (EIT) at both PEEP levels.

2. Methods

The study protocol was approved by the ethics committee of the University of Freiburg (EK35/14) and registered at the German Register for Clinical Studies (DRKS00006033) before inclusion of the first patient. Written informed consent was obtained from all parents prior to the procedure. The study included 40 children (ASA status I–II, age 11–168 months), who consecutively underwent elective ENT surgery with a planned surgery duration >60 min at the University Medical Center Freiburg. Exclusion criteria were age over 12 years or below 3 months, known lung disease, cardiac pacemaker, implantable cardioverter or defibrillator, or other active implants, intracardiac heart defects, planned oblique or prone position, surgery close to the thorax, and abdominal procedures. Midazolam (0.2 mg g^{-1} body weight, Dormicum®, Roche Pharma AG, Grenzach-Wyhlen, Germany) was administered as oral premedication at least 1 h before inducing anaesthesia. EIT gives functional images of regional lung ventilation based on the reconstruction of regional electrical impedances within the axial plane of interest. Therefore, small currents are applied via circumferential electrodes and the voltage distribution at the body surface is measured. (Frerichs et al., 2001) To conduct the EIT measurements, a belt with 16 electrodes was placed around the rib cage at the level of the 5th intercostal space. After implementing routine monitoring (ECG, $SpaO_2$, non-invasive blood pressure measurement, Infinity Delta XL, Dräger Medical, Lübeck, Germany) an intravenous line was placed and the anaesthesia was induced according to a standard protocol. Remifentanil (Janssen-Cilag, Germany) 0.3–0.5 $\mu g\,kg^{-1}\,min^{-1}$ and Propofol 1% (Fresenius Kabi, Germany) 2–3 mg kg^{-1} were administered to induce anaesthesia. Maintenance of anaesthesia was provided total intravenously by administration of Propofol 100–150 $\mu g\,kg^{-1}\,min^{-1}$ and continuous infusion of Remifentanil 0.1–0.2 $\mu g\,kg^{-1}\,min^{-1}$. Cisatracurium (0.2 mg/kg^{-1}, Nimbex®, GlaxoSmithKline, Munich, Germany) was administered for relaxation during tracheal intubation. Neuromuscular monitoring was conducted by mechanomyography (Stimpod NMS450, Xavant Technology Ltd, South Africa), incremental doses of Cisatracurium (0.02–0.03 mg kg^{-1}) were given whenever the train of four count returned to 1–2, and neuromuscular block was maintained until the surgery procedure was finished. Intraoperative fluids were administered as a crystalloid solution (8 ml $kg^{-1}\,h^{-1}$, Jonosteril, Fresenius Kabi, Germany). Bispectral index (BIS, Aspect Medical Systems, Newton, MA, USA) electrodes were placed on the patient's forehead to measure the depth of anaesthesia. The BIS index was maintained between 40 and 60 during the entire measurement procedure. The ventilation protocol consisted of volume-controlled ventilation (Primus IE, Dräger Medical, Lübeck, Germany) with an inspiratory to expiratory ratio of 1:2, tidal volume of 8 ml kg^{-1}, and respiratory rate set to maintain normocapnia (end-tidal carbon dioxide partial pressure between 4 and 5.3 kPa). After transfer to the operation theatre, the children were randomly assigned to one of two cross-over groups receiving mechanical ventilation either with a PEEP of 2 cmH_2O for 20 min followed by a PEEP of 5 cmH_2O for 20 min or vice versa, while the planned surgery was performed. The position of the patients was not changed during the measurement period. Flow rate and airway pressure as measured by the ventilator were recorded using a self-developed software based on LabView (v7.1, Austin, TX, USA) with a sample rate of 62.5 Hz. EIT data were recorded at a rate of 50 frames per second (PulmoVista® 500, software version 1.10, Dräger, Lübeck, Germany). In addition, oxygen saturation, heart rate, non-invasive blood pressure, and end-tidal partial pressure of carbon dioxide were protocolled at 5-min intervals during the entire procedure.

2.1. Data analysis

The analyses were made offline using Matlab (R 2012, Natick, MA, USA) or Excel (Excel 2010, Microsoft, Redmond, WA, USA). PEEP might influence compliance and as a consequence the driving pressure which is the pressure difference between end and beginning of inspiration (Amato et al., 2015). The dynamic compliance of the respiratory system (C_{RS}) at the different PEEP levels was calculated for every patient and driving pressure was calculated as the Quotient of tidal volume and compliance (Amato et al., 2015). Using the gliding-SLICE method, the volume-dependent compliance curves were calculated (Buehler et al., 2014; Guttmann et al., 1994; Schumann et al., 2009). In brief: the intratidal pressure-volume curve was divided into 21 equidistant volume segments. In a multiple linear regression analysis, the volume-specific compliance was calculated from the data surrounding each segment (SLICE) within the range of $\pm 1/12$ of the tidal volume. The resulting compliance-volume curves were considered as a section of the patient's overall compliance curve across the vital capacity. They were classified and assigned to one of 6 compliance profiles (Wirth et al., 2015). A merely increasing (I) profile, was considered to indicate strong intratidal recruitment/derecruitment. A merely decreasing (D) profile was considered to indicate strong overdistension. For a horizontal (H) profile, it was assumed that there was neither derecruitment nor overdistension. Three other possible profiles result from the combinations of those basic profiles: an increasing turning into horizontal (IH) profile was considered to indicate moderate intratidal recruitment/derecruitment, a horizontal turning into decreasing (HD) profile was considered to indicate moderate intratidal overdistension and a profile ranging from increasing via horizontal to decreasing (IHD) was considered to indicate both, intratidal recruitment/derecruitment and overdistension.

From the EIT data, images representing tidal ventilation were calculated by pixel-wise subtraction of the end-expiratory impedance values from the end-inspiratory ones. To define a general measure for localization of ventilation, the centres of ventilation (COV) of the tidal images were calculated. The COV was defined as the horizontal and vertical balance point in the image, i.e. the horizontal and vertical position at which the sums of the relative impedance changes above and below, respectively left and right were equal. A change in the COV would identify a left-right of ventral dorsal shift of regional ventilation.

2.2. Statistical analysis

The frequencies of profiles were compared with a chi-square test. Before performing comparisons of variables at different PEEP levels their normal distribution was confirmed with a Lilliefors test. Differences in the mean values of the variables between different PEEP conditions were tested using repeated measures ANOVA followed by Fisher's PLSD post hoc test if appropriate. A $p < 0.05$ was considered to be statistically significant. Unless indicated otherwise, the data are reported as mean (SD). In the EIT, the statistical analysis of the relative pixel-wise change in impedance between