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Clinical Investigation

CLINICAL INVESTIGATION

Validation of capnodynamic determination of cardiac output by measuring effective pulmonary blood flow: a study in anaesthetised children and piglets

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Abstract

Background: Effective pulmonary blood flow (CO_{EPBF}) has recently been validated as a technique for determining cardiac output (CO) in animals of varying sizes. The primary aim of our study was to investigate this new technique in paediatric surgical patients, compared with suprasternal two-dimensional Doppler (CO_{SSD}).
Methods: A total of 15 children undergoing cleft lip/palate surgery were investigated. Before the start of surgery, manoeuvres that were anticipated to reduce (increase in PEEP from 3 to 10 cm H_2O) and increase (atropine) CO were undertaken. A study in mechanically ventilated piglets was also undertaken under general anaesthesia, measuring CO_{EPBF} and pulmonary artery (CO_{TS}) flow by ultrasonic probe as the comparator. Bias (Bland–Altman plots) and limits of agreement were assessed for effective pulmonary blood flow and CO_{SSD} or CO_{TS}.
Results: In paediatric patients (median age 8.5 months), overall bias was −8.1 (limits of agreement −82 to +66) ml kg^{-1} min^{-1}, with a mean percentage error of 48% and a concordance rate of 64%. In the piglet model, overall bias was −1 (−36 to +38) ml kg^{-1} min^{-1}, with a mean percentage error of 31% and a concordance rate of 95%.
Conclusions: Under controlled experimental conditions, CO_{EPBF} is associated with excellent agreement and good trending ability when compared with the gold standard CO_{TS}. In the paediatric clinical setting, CO_{EPBF} performs well; by contrast, CO_{SSD}, an operator- and anatomy-dependent technology, appears less reliable than CO_{EPBF}.

Keywords: carbon dioxide; cardiac output; child; pulmonary artery; ultrasonic

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Editor's key points

- Effective pulmonary blood flow (CO_{EPBF}) is a validated, non-invasive technique for determining cardiac output (CO) in small, mechanically ventilated animals.
- Routine measurement of CO in anaesthetised paediatric patients is limited by technological constraints and the avoidance of invasive techniques.
- This study shows high concordance between CO_{EPBF} and the gold standard measurement of pulmonary blood flow (by ultrasonic flow probe) in anaesthetised, mechanically ventilated piglets.
- In the paediatric clinical setting, the authors also showed that CO_{EPBF} detected CO changes in mechanically ventilated, anaesthetised children.

The ability to monitor cardiac output (CO) is of great interest in many medical specialties, but is of specific importance in the context of anaesthesia and intensive care. In the adult setting, a variety of techniques have been advocated to monitor CO, but all have significant limitations when applied clinically. This is perhaps even more apparent in infants and small children, as many techniques cannot be safely used or suffer from paediatric-specific constraints.[1] Furthermore, few of these techniques have been validated in infants and children.[2]

The continuous capnodynamic approach to determine CO (effective pulmonary blood flow, CO_{EPBF}) in intubated, mechanically ventilated patients, has recently been validated in porcine experiments.[3–5] Studies of previous CO_2 based CO measurement techniques have found the methods to be in acceptable agreement with gold standard comparators (e.g. pulmonary artery catheter thermodilution) and associated with excellent trending characteristics.[6–9] However, the CO_{EPBF} method has not been studied in the clinical setting.

The primary aim of the present study was to compare the performance of CO_{EPBF} in children undergoing anaesthesia with a clinically accepted measure [suprasternal two-dimensional (2D) Doppler CO].[10–12] A porcine study was also undertaken to further explore this clinical protocol, using an ultrasonic flow probe as the gold standard measure of pulmonary artery blood flow.[13]

Methods

Clinical investigation

This part of the study was performed at the Karolinska University Hospital, Stockholm, Sweden. After Internal Ethical Review Board approval (number 2015-551/31, Chairman Hans Glauman) and Parental Informed Consent (verbal and written), 15 paediatric patients, undergoing surgical cleft lip-palate repair, were enrolled. Exclusion criteria were: concomitant systemic illness, known heart disease, ongoing medication, and ASA risk class III–IV.

Induction of anaesthesia was either by inhalation (sevoflurane) or i.v. (propofol). Anaesthesia was maintained using propofol 15 mg kg^{-1} h^{-1}, fentanyl 1 μg kg^{-1}, and rocuronium 0.6 mg kg^{-1}. After preoxygenation (FiO_2: 1.0), the airway was secured using a cuffed tracheal tube of age adequate dimension (Microcuff® Pediatric ETT, Kimberly Clark, Health Care, Atlanta, GA, USA) with the cuff inflated to allow an adequate airtight seal at a cuff pressure of 15–20 cm H_2O. After tracheal intubation, the patient was connected to a ventilator equipped with additional software creating the breathing pattern required for EPBF determination (Servo I, Maquet Critical Care, Solna, Sweden). This was subsequently followed by a standardised lung recruitment manoeuvre, using FiO_2 0.3, PEEP 8 cm H_2O and tidal volumes (TV) 6–8 ml kg^{-1} for 2 min. This ventilatory strategy was undertaken to minimise atelectasis caused by apnoea and muscle relaxation during tracheal intubation. Ventilation was maintained using pressure control, FiO_2 0.3, PEEP 3 cm H_2O, TV 6–8 ml kg^{-1} and a ventilatory frequency adjusted to ensure normocapnia (end-tidal CO_2: 4.5–6.7 kPa). Before initiation of the study protocol, a transthoracic echocardiographic examination (Philips CX 50, S8-3 probe Philips Healthcare, Andover, MA, USA) was undertaken to rule out the presence of cardiac shunts.

Study protocol

After a 5-min stabilisation period following tracheal intubation, the study sequence was performed (Fig. 1):

(i) Three baseline CO measurements were performed 1 min apart. CO_{SSD} and CO_{EPBF} were recorded simultaneously.
(ii) To reduce CO, PEEP was then increased from 3 to 10 cm H_2O. CO measurements were performed at 1, 3, and 5 min after the PEEP increase.
(iii) Further recordings of CO were undertaken at 1 and 3 min after PEEP had been restored to 3 cm H_2O.
(iv) To increase CO, the patients were then given an i.v. bolus of atropine 20 μg kg^{-1} which is part of the standard anaesthetic for these patients. CO_{EPBF} and CO_{SSD} were then recorded 1, 3, and 5 min after atropine administration, which completed the experimental protocol. Thereafter, anaesthesia and surgery continued according to routine clinical management.

Cardiac output measurements

CO_{EPBF}

CO_{EPBF} was measured continuously, as described by Hällsjö and colleagues[3] using the differential Fick's principle. The continuous method is based on the molar balance for CO_2 as described in Equation (1):

$$ELV\left(FACO_2^n - FACO_2^{n-1}\right) = EPBF\,\Delta\,t^n\left(C_vCO_2 - C_cCO_2^n\right) - VTCO_2^n \quad (1)$$

ELV, effective lung volume (litre) containing CO_2 at the end of expiration; EPBF, effective pulmonary blood flow (litre min^{-1}); n, current breath; n−1, previous breath; F_ACO_2, alveolar CO_2 fraction; C_vCO_2, venous CO_2 content ($litre_{gas}$/$litre_{blood}$); $C_cCO_2^n$, lung capillary CO_2 content (calculated from F_ACO_2); $VTCO_2^n$, volume (litre) of CO_2 eliminated by the current, *n*th, breath; $\Delta\,t^n$, current breath cycle time (min).

By constantly changing the inspiratory and expiratory relationship in a preset rhythm of six breaths with inspiratory/expiratory relationship of 1:2, followed by three breaths with an extended expiratory pause (2 s, causing a functional lower ventilatory frequency), alveolar CO_2 concentration changes approximately 0.5–1 kPa.[14] This change in alveolar CO_2 concentration and elimination is proportional to the alveolar blood flow, as described in Equation (1). Each breathing analysis