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Evaluation of a novel automated non-invasive pulse pressure variation algorithm

Martin Schmid [a], Helga Prettenthaler [b], Christian Weger [c], Karl-Heinz Smolle [b,*]

[a] Institute for Medical Engineering, University of Technology Graz, Austria
[b] Department of Internal Medicine and Intensive Care, University Hospital Graz, Austria
[c] Department of Orthopaedic Surgery, University Hospital Graz, Austria

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ABSTRACT

In mechanically ventilated patients, Pulse Pressure Variation (PPV) has been shown to be a useful parameter to guide fluid management. We evaluated a real-time automated PPV-algorithm by comparing it to manually calculated PPV-values. In 10 critically ill patients, blood pressure was measured invasively (IBP) and non-invasively (CNAP® Monitor, CNSystems Medizintechnik, Austria). PPV was determined manually and compared to automated PPV values: PPV_{manIBP} vs. $PPV_{autoIBP}$ was $-0.19 \pm 1.65\%$ (mean bias ± standard deviation), $PPV_{manCNAP}$ vs. $PPV_{autoCNAP}$ was $-1.02 \pm 2.03\%$ and $PPV_{autoCNAP}$ vs. PPV_{manIBP} was $-2.10 \pm 3.14\%$, suggesting that the automated CNAP® PPV-algorithm works well on both blood pressure waveforms but needs further clinical evaluation.

1. Introduction

Several outcome-related studies have demonstrated that goal-directed fluid administration (where the amount of fluid given during surgery and on intensive care units is sought to be optimized based on an objectively quantifiable variable as opposed to supplying fluid on a general basis) can significantly improve the outcome for the patient [1–3]. Recently, the approach of functional hemodynamic monitoring in sedated patients receiving mechanical ventilation has become the preferred option to predict fluid responsiveness (i.e., whether or not the patient reacts with significantly increased cardiac output to fluid administration, thus indicating fluid depletion) [4]. Dynamic indicators have been demonstrated to be better predictors of fluid responsiveness than static parameters [5–7]. Among these dynamic indices, the variation of pulse pressure (PPV), i.e. the variation of the difference between systolic and diastolic blood pressure, has been shown to be more reliable than other dynamic parameters [8] and is already used for clinical fluid management [9].

PPV can be calculated based on blood pressure waveforms detected with an intra-arterial catheter or based on non-invasive blood pressure signals (e.g. CNAP® Monitor). Manual off-line calculation of PPV is considered the "gold standard" in medical literature [10]. In general, continuous blood pressure and also airway pressure signals are required for this calculation. To eliminate the need for simultaneously acquiring airway pressure from the ventilator, elaborate algorithms have been designed to automatically and continuously estimate PPV from the blood pressure signal alone [11]. Most of them are based on invasive blood pressure waveforms and show high accuracy [12,13].

Reliable PPV-values can also be derived manually from non-invasive blood pressure waveforms [14] which may be useful especially in patients without the indication for an arterial catheter. The CNAP® non-invasive blood pressure monitor has recently been validated in patients undergoing general anesthesia for abdominal, gynecological, vascular and neurosurgical procedures [15,16]. The results show good accuracy when comparing beat-to-beat blood pressure measurements to their invasive counterparts. The ability of manually calculated PPV based on blood pressure waveforms obtained with the CNAP® device to predict fluid responsiveness has already been evaluated during vascular surgery [17] and in critically ill patients [18]. In their article, Biais et al. [17] derived PPV manually from the CNAP® blood pressure waveform and compared it to PPV derived from invasive measurements of an ipsilateral radial catheter, while Monnet et al. [18] compared manually calculated PPV of the CNAP® waveform to PPV derived from invasive measurements of a femoral catheter. Their results suggest that the amplitude of the respiratory-induced variations in the pulse pressure in the finger can predict fluid

* Corresponding author. Tel.: +43 316 385 81414.
E-mail addresses: karlheinz.smolle@klinikum-graz.at, karl-heinz.smolle@klinikum-graz.at (K.-H. Smolle).

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responsiveness with a similar sensitivity and specificity as PPV derived from invasive readings, both for surgical and intensive care patients.

In this work, we evaluate the automated CNAP® PPV algorithm itself which is used for displaying PPV-values automatically and continuously on the CNAP® device. The goal of this study was the comparison of manually calculated PPV values to PPV values derived automatically via the PPV algorithm of the CNAP® Monitor using both invasive as well as non-invasive blood pressure waveforms as a basis.

2. Methods

The study protocol was approved by the ethics commission for human subjects (University Hospital Graz, Austria). All patients or their relatives were informed about the study when the patient was included and could refuse the patient′s participation at any time. We studied 10 patients on the medical intensive care unit who were all sedated, under vasopressor therapy (norepinephrine) and had sinus rhythm. Patients with obvious edema on the upper extremeties, especially the fingers, were not included in the study. Invasive arterial blood pressure (IBP) was monitored via a radial artery catheter (20G, Arterial Cannula, BD Critical Care Systems Ltd., Singapore). Damping coefficient and natural frequency of the hydrostatic transducer system was tested using the fast flush test [19]. All patients were mechanically ventilated with an Evita XL (Dräger, Germany) in the Biphasic Positive Airway Pressure (BiPAP) mode. Blood pressure signals only of patients without signs of spontaneous breathing were examined since spontaneous respiration has been shown to be ineffective in producing reliable changes in the arterial waveform to guide fluid management [20].

The CNAP® system (CNAP® Monitor 500, CNSystems Medizintechnik AG, Graz, Austria) consists of a double finger cuff, a pressure transducer mounted on the forearm and an upper-arm blood pressure cuff for calibration. The principle of CNAP®, the "volume clamp method" (or "vascular unloading technique") was originally developed by Peňáz [21] in the early 1970s and further improved by Fortin et al. [22]. A finger cuff encompassing two neighboring fingers (see Fig. 1) is used for continuous non-invasive blood pressure monitoring, one finger at a time with automatic switches between fingers every 5–60 min (set to 30 min for this study as recommended by the manufacturer). An upper-arm blood pressure cuff derives the measurement of oscillometric blood pressure and serves for calibration of the device every 5–60 min (set to 15 min for this study as recommended by the manufacturer).

The CNAP® finger cuff was placed contralaterally to the invasive catheter. The CNAP® upper-arm cuff was applied to the same arm as the invasive catheter to eliminate possible pressure differences of the arms. While such pressure differences are unimportant when studying only PPV, they might affect comparing BP levels between IBP and CNAP® directly. IBP and CNAP® transducers were placed approximately at the level of the heart. The CNAP® Monitor was connected to the patient monitor and zero-levelled as recommended by the manufacturer.

CNAP® and IBP blood pressure waveforms were synchronously displayed on the bedside patient monitor (Infinity Delta, Dräger, Germany) and recorded using data acquisition software (Dräger DataGrabber) which allows the export of CNAP® and IBP systolic, diastolic and mean blood pressure values and the blood pressure waveforms with a sampling rate of 100 Hz. All off-line data analyses were performed using MATLAB-based scripts (Matlab R2008b, The Math Works Inc., Natick, MA, USA).

So that all patients contribute equally to the results, all comparison analyses were based on the same number of PPV values per patient. For the manually calculated PPV values, the following

Fig. 1. CNAP® monitor showing the double finger cuff, the pressure transducer mounted on the forearm and the upper-arm blood pressure cuff.

procedure was performed: Using a random number generator, 10 time periods of the waveform data were analyzed for each of the 10 patients. At randomly generated points of time, the two blood pressure waveforms were visually checked for artifacts at a length of 38 heart beats. This number of heart beats was chosen because it is longer than 3 typical respiratory cycles. If both the invasive as well as the non-invasive waveforms were visually considered artifact-free, the following procedure was performed: The "gold standard" reference PPV values were calculated by manually selecting three consecutive pulse pressure minima and maxima per mouse-click (see Fig. 2) and using the standard formula as described in the literature [10]: $PPV = (PP_{max} - PP_{min})/[(PP_{max} + PP_{min})/2] \times 100\%$. The PPV_{man} value was defined as the average PPV over these three consecutive respiratory cycles. PPV_{man} was thus calculated retrospectively based on the IBP and CNAP® blood pressure waveforms. For every patient, this procedure was repeated until 10 value pairs (PPV_{manIBP} and $PPV_{manCNAP}$) were obtained over the same time periods (marked with their end time points $T_1 - T_{10}$).

These PPV_{man} values were compared to PPV_{auto} values which would have been displayed on the CNAP® Monitor at time points $T_1 - T_{10}$. These PPV_{auto} values were retrospectively obtained using a software extract provided by the manufacturer. Basically, the proprietary PPV algorithm integrated into the CNAP® monitor automatically searches for the typical swing patterns in the blood pressure waveform modulated by mechanical respiration. PPV values are computed by employing automated detection of pulse pressure minima and maxima and using the standard PPV formula (see above) before being smoothed using an average over 3 consecutive respiratory swings. Additionally, an update filter with an adaptive coefficient corrects for abnormally strong physiological changes in PPV and is applied before displaying the final PPV value on the CNAP® monitor. The original algorithm part for