Novel Technology

Noninvasive Central Venous Pressure Measurement by Controlled Compression Sonography at the Forearm

Christoph Thalhammer, MD,* Markus Aschwanden, MD,* Angela Odermatt,*
Ulrich A. Baumann, MD,§ Stephan Imfeld, MD,* Deniz Bilecen, MD, PHD,†
Stephan C. Marsch, MD, PHD,‡ Kurt A. Jaeger, MD*

Basel and Muensingen, Switzerland

Objectives   We sought to validate a new noninvasive technique to determine central venous pressure (CVP) using high-resolution compression sonography.

Background   Information concerning CVP is crucial in clinical situations, including cardiac failure, volume overload, and sepsis. The measurement of CVP, however, requires puncture of a vein with attendant risk of complication.

Methods   After a proof-of-concept study in healthy subjects, a prospective blinded evaluation was performed comparing CVP measurement using a central venous catheter with measurement using compression sonography in critically ill (intensive care unit) patients.

Results   In healthy subjects with experimentally induced venous hypertension with a wide range of pressure values, a strong correlation (r = 0.95; p < 0.001) between noninvasive and invasive peripheral venous pressure at the forearm was shown. High interobserver agreement with an intraclass correlation coefficient of 0.988 shows excellent reliability of the system. Noninvasive peripheral venous pressure measurement at the forearm showed a good correlation with CVP in 50 intensive care unit patients with the forearm positioned both below heart level (r = 0.84; p < 0.001) and at heart level (r = 0.85; p < 0.001). The mean difference between invasive and noninvasive measurement was negligible (−0.1 ± 3.5 cm H_2O and −0.7 ± 3.4 cm H_2O, respectively).

Conclusions   Controlled-compression sonography is a valuable tool for measuring venous pressure in peripheral veins and allows reliable indirect assessment of CVP without intravenous catheterization.   (J Am Coll Cardiol 2007;50: 1584–9) © 2007 by the American College of Cardiology Foundation

Central venous pressure (CVP) measurement is essential for monitoring hemodynamics in critically ill patients and during surgery to estimate cardiac preload and circulating blood volume. Clinical estimation of CVP has proven unreliable compared with measurement using a catheter (1). The current standard technique for measurement of CVP is invasive, requiring insertion of a catheter into a subclavian or internal jugular vein, with potential complications (2). A quick and reliable tool for monitoring CVP without need of central venous access would be helpful. Recently published studies have shown good correlation between peripheral venous pressure (PVP) and CVP, which allowed accurate assessment of CVP under a variety of conditions (3–5).

We report on a new tool for noninvasive venous pressure measurement using high-resolution ultrasound imaging combined with a translucent pressure manometer. The controlled compression sonography was applied at the forearm, and results were compared with the gold standard of invasive venous pressure measurement in both healthy subjects and patients from an intensive care unit (ICU).
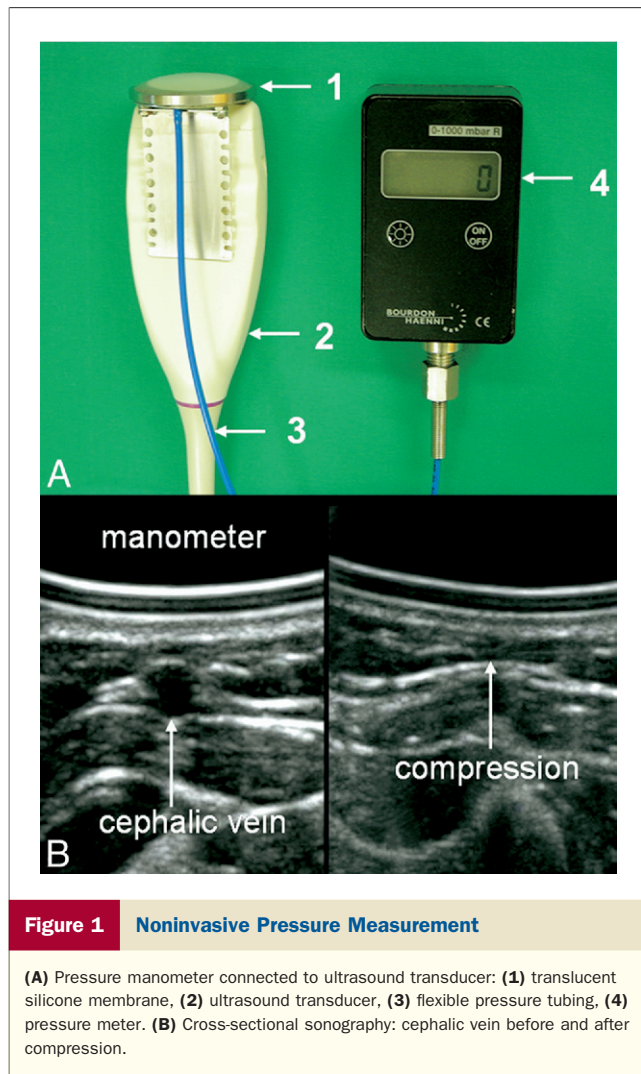
In a first phase, we performed a proof of concept study in healthy subjects to show that: 1) PVP can be measured with the ultrasound system; and 2) induced changes in venous pressure can be reliably documented. In a second phase we applied the system to ICU patients to test feasibility and accuracy for measuring CVP by the ultrasound system using peripheral forearm veins either at heart level or below.

Methods

Description of the system. Ultrasound imaging was performed by 2 experienced investigators (C.T. and M.A.)

Figure 1   **Noninvasive Pressure Measurement**

(A) Pressure manometer connected to ultrasound transducer: (1) translucent silicone membrane, (2) ultrasound transducer, (3) flexible pressure tubing, (4) pressure meter. (B) Cross-sectional sonography: cephalic vein before and after compression.

were included. All volunteers had normal blood pressure (122 ± 12/75 ± 9 mm Hg) and heart rate (73 ± 10 beats/min); mean body mass index (BMI) was 20.0 ± 2.4 kg/m². The study was performed in a quiet and temperature-controlled room. The volunteers were placed in a comfortable supine position with a slightly elevated chest and were breathing regularly. Venous puncture site was localized on the average 20 cm below the level of the right atrium. The PVP measurements were done after a resting period of 15 min.

ICU patients. A total of 58 patients treated in the ICU were consecutively screened for eligibility. A continuous cardiovascular monitoring with CVP measurement was clinically indicated. Exclusion criteria for the study were: not compressible, not visible, or extremely thin (<0.5-mm diameter) superficial veins (n = 7); refused informed consent (n = 0); agitation (n = 1); and known thrombosis of the upper extremity (n = 0). Fifty patients were finally included; demographics are presented in Table 1. The investigators were blinded for CVP, diagnosis, therapy, and volume status of the patients.

Proof of concept in healthy subjects. NONINVASIVE PVP MEASUREMENT. Elicited venous hypertension was induced by changing inflation pressure of a sphygmomanometer cuff at the upper arm in steps of 5 mm Hg. Cuff pressure was randomly changed from 0 to 50 mm Hg by a study nurse. Independent examination of each subject by 2 sonographers allowed the assessment of interobserver variation. Pressure values were recorded by the nurse. Sonographers were blinded for all pressure values. Mean values of 3 measurements per investigator were calculated and used for further analysis.

**Abbreviations
and Acronyms**

BHL = below heart level

BMI = body mass index

CVP = central venous pressure

HL = heart level

ICU = intensive care unit

PVP = peripheral venous pressure

PVPi = invasive peripheral venous pressure

PVPn = noninvasive peripheral venous pressure

using a HDI 5000 duplex device (Philips, Best, the Netherlands) with a 5- to 12-MHz transducer (SonoCT, XRes, Philips). A pressure manometer (PPM0310, Baumann, Muensingen, Switzerland) was attached to the transducer (Fig. 1A). The manometer consists of a translucent silicon membrane (MVQ, Angst and Pfister AG, Zurich, Switzerland) connected to a pressure meter (Bourdon Haenni AG, Jegenstorf, Switzerland) with flexible pressure tubing. After applying ultrasound transmission gel, the transducer with the pressure meter was placed on the skin with minimal pressure. The vein had to be easily compressible and without post-phlebitic changes. After zero adjustment, slowly increasing pressure was applied by the transducer until complete compression of the vein (Fig. 1B). The pressure at that collapse point corresponds to the intravasal venous pressure.

Healthy subjects. The system was tested in the cephalic vein at the right forearm. Noninvasive PVP (PVPn) was measured in a model with induced venous hypertension and compared with measurement by invasive PVP (PVPi). Ten healthy volunteers (5 women, 5 men), ages 23 to 59 years (median 33 years) without cardiovascular risk factors

Table 1   **Patients Characteristics**

	Intensive Care Unit Patients (n = 50)
Age (yrs), median (range)	69 (17–85)
Male gender	31 (62%)
Body mass index (kg/m²)	27.9 ± 4.2 (18.8–51.4)
Critical illness	
Sepsis	12 (24%)
Cardiac failure	10 (20%)
Myocardial infarction	9 (18%)
Pneumonia	5 (10%)
Metabolic disorders	4 (8%)
Cardiac arrhythmias	3 (6%)
Epilepsia	3 (6%)
Others*	4 (8%)

*Including gastrointestinal bleeding, pulmonary embolism, cerebral bleeding, and pancreatitis.

INVASIVE PVP MEASUREMENT. The cephalic vein of the right forearm was punctured with a 20-gauge intravenous catheter (Optiva 2, Johnson & Johnson Medical, New Brunswick, New Jersey). The catheter was connected to a vertical water column with a connection conduit (Clinico, Bad Hersfeld, Germany) and a 3-way tap (Connecta Plus 3, Becton Dickinson, Helsingborg, Sweden). The system was flushed by infusion of 0.9% NaCl solution (B. Braun Medical AG, Emmenbruecke, Switzerland) between single measurements. Zero adjustment of the system with a scale at the water column was done at the level of the puncture site of the venous catheter. Mean values of 3 measurements per investigator were obtained and used for further analyses.

Venous pressure measurement in ICU patients. PVPN MEASUREMENT. The PVPn was measured on the contralateral side of the central venous catheter to avoid falsely elevated values caused by obstruction through the catheter. The PVPn measurement was done at the site of a best visible superficial vein at the forearm with the point of measurement and calibration usually below the level of the right atrium (below heart level [BHL]). The difference between the level of the sonographic measurement point and the heart was documented, and the forearm was elevated to the level of the heart (heart level [HL]). A second measurement series at HL was performed after new calibration of the system. The BHL measurements were done under the hypothesis that the veins would be better filled and thus better visible in this position. Additionally, BHL position corresponds more closely to real-life conditions. The HL distance in centimeters was subtracted from the BHL values for correction of the blood column height.

Invasive CVP measurement. In ICU patients, central venous catheters at the subclavian venous site or the internal jugular vein had been inserted (Arrow International, Reading, Pennsylvania). A cardiovascular monitor measured CVP with an effective range of -5.3 to 48 kPa and a precision of 3% (product information; Agilent M1165, Agilent Technologies, Andover, Massachusetts). Mean values of 3 successive CVP measurements per investigation were calculated and analyzed.

Study protocol. The study was approved by the local ethics committee. Healthy subjects of the pilot study gave written informed consent. Sentient intensive care patients provided oral informed consent. Surrogates provided informed consent for intubated, nonsentient ICU patients. The physician in charge of the intensive care attested to the safety of the investigation for the patient.

Statistical analysis. Data analysis was performed using SPSS 12.0 (Apache Software Foundation, Forest Hill, Maryland). To observe whether changes in invasive pressure were paralleled by simultaneous changes in noninvasive pressure, intrasubject correlation was assessed by linear regression. Correlation between invasive and noninvasive pressures was analyzed using Spearman correlation coefficient r. The unit of pressure values was centimeters of H_2O. Descriptive data were expressed as the mean ± standard

deviation or median and range. Bland-Altman plots were used to show the agreement between PVPi and PVPn in healthy subjects, as well as between CVP and PVPn in the ICU patients, plotting the difference against the mean (6). A clinically acceptable limit of agreement was defined as 4 cm H_2O ($\cong$3 mm Hg) between CVP and PVPn (4). Differences in correlation coefficients are tested for significance using a Fisher z transformation.

Results

Proof of concept in healthy subjects. The mean internal diameter of the vein at rest was 3.3 ± 0.6 mm and 4.3 ± 0.5 mm at a cuff pressure of 50 mm Hg. Mean PVPi without cuff inflation was 19.6 ± 4.7 cm H_2O (range 11.3 to 29.3 cm H_2O). Elicited venous hypertension induced by increasing the pressure of the cuff at the upper arm resulted in a linear increase in PVPi, if cuff pressure exceeded a threshold of 15 mm Hg (Fig. 2). The maximal PVPi was 67.8 ± 6.9 cm H_2O (range 57.7 to 77.7 cm H_2O) with a cuff pressure at the upper arm of 50 mm Hg. The interobserver agreement for PVPn was high, with an intraclass correlation coefficient of 0.988 (95% confidence interval 0.984 to 0.991) (Fig. 2). Linear regression analysis showed a significant positive correlation between PVPi and PVPn (r = 0.95; p < 0.001) (Fig. 3A). A high correlation between PVPi and PVPn was observed for each of the 2 investigators, with a correlation coefficient of 0.94 for investigator 1 (p < 0.001; regression line y = 0.84x + 8.0) and 0.96 for investigator 2 (p < 0.001; regression line y = 0.86x + 4.1). The mean difference of PVPi and PVPn in all measurements was negligible (+0.80 ± 6.14 cm H_2O, range −26 to 15 cm H_2O). The Bland-Altman plot shows the differences between PVPi and PVPn data plotted against their mean (Fig. 3B). Some single-pressure values were overestimated by the noninvasive technique in very high venous pressure ranges (>70 cm H_2O).

Venous pressure measurement in ICU patients. BHL MEASUREMENTS. The mean internal diameter of the vein was 2.4 ± 0.8 mm (range 0.9 to 4.5 mm). The mean CVP was 12.4 ± 4.7 cm H_2O (range 5.0 to 25.3 cm H_2O) and mean PVPn was 12.5 ± 6.3 cm H_2O (range 0.7 to 30.0 cm H_2O). The calibration point was 5.4 cm below heart level (range 0 to 14 cm). Linear regression analysis showed a positive correlation between CVP and PVPn (r = 0.84; p < 0.001) (Fig. 4A). The mean difference of CVP and PVPn was negligible (−0.1 ± 3.5 cm H_2O, range −10.3 to 6.2 cm H_2O). The Bland-Altman plot shows the differences between CVP and PVPn data plotted against their mean (Fig. 4B). The influence of training and routine is documented in Table 2, in which the results of the first 29 patients are compared with the second part of the patient population. Agreement increased from 67% to 95% in the course of the study (Table 2). Corresponding to that agreement, range and standard deviation decreased in the last investigations, resulting in a stronger correlation.

HL MEASUREMENTS. Mean internal diameter of the vein was 2.2 ± 0.9 mm (range 0.5 to 3.9 mm). Mean CVP measured was 12.9 ± 5.3 cm H_2O (range 5.0 to 27.3 cm H_2O) and mean PVPn at heart level was 13.6 ± 6.4 cm H_2O (range 3.3 to 32.7 cm H_2O). Linear regression analysis showed a positive correlation between CVP and PVPn (r = 0.85; p < 0.001) (Fig. 5A). The mean difference of CVP and PVPn was negligible (-0.7 ± 3.4 cm H_2O, range -8.7 to 8.7 cm H_2O). The Bland-Altman plot shows the differences between CVP and PVPn data plotted against their mean (Fig. 5B). Agreement of CVP and PVPn
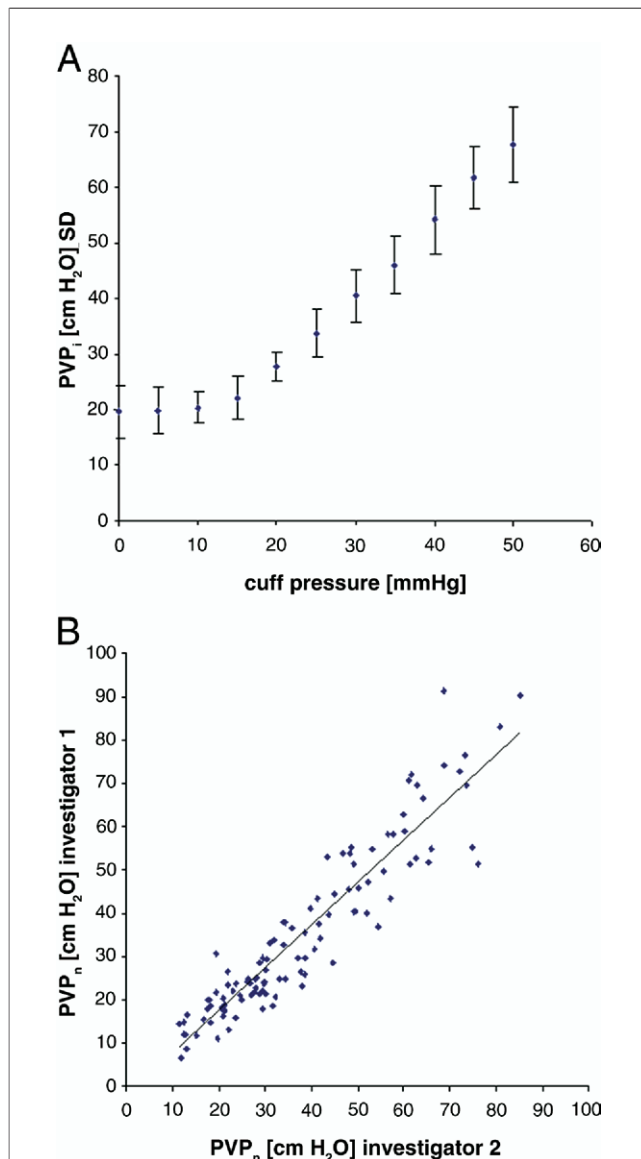
Figure 2   **Artificial Venous Hypertension and Interobserver Agreement**

(A) Venous hypertension. Mean invasive peripheral venous pressure (PVPi) without cuff compression was 19.6 ± 4.7 cm H_2O, followed by a linear increase in PVPi above a cuff pressure of 15 mm Hg. Maximal PVPi was 67.8 ± 6.9 cm H_2O. **(B)** Interobserver agreement: intraclass correlation coefficient was 0.988. PVPn = noninvasive peripheral venous pressure.
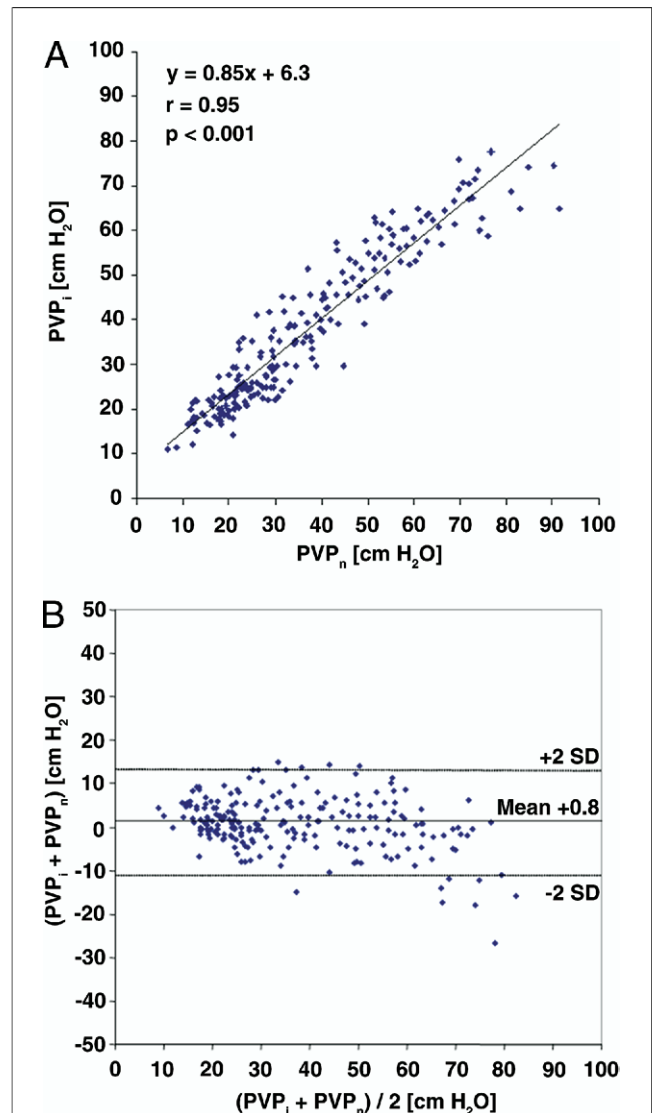
Figure 3   **PVPi and PVPn in Healthy Subjects**

(A) Linear regression: positive correlation between PVPi and PVPn. **(B)** Bland-Altman plot: PVPi and PVPn plotted against their mean. Abbreviations as in Figure 2.

increased from 59% to 100% in the course of the study with decreasing range and standard deviation (Table 3), resulting in a increase of the correlation coefficient.

Discussion

A novel noninvasive method using controlled compression sonography was proven to measure PVP and CVP in a simple, reliable, and reproducible manner. The important finding of this study was a strong correlation of PVPn to PVPi in experimental venous hypertension with a wide range of venous pressure between 10 and 70 cm H_2O. Furthermore, high interobserver agreement showed the excellent reliability of the system.
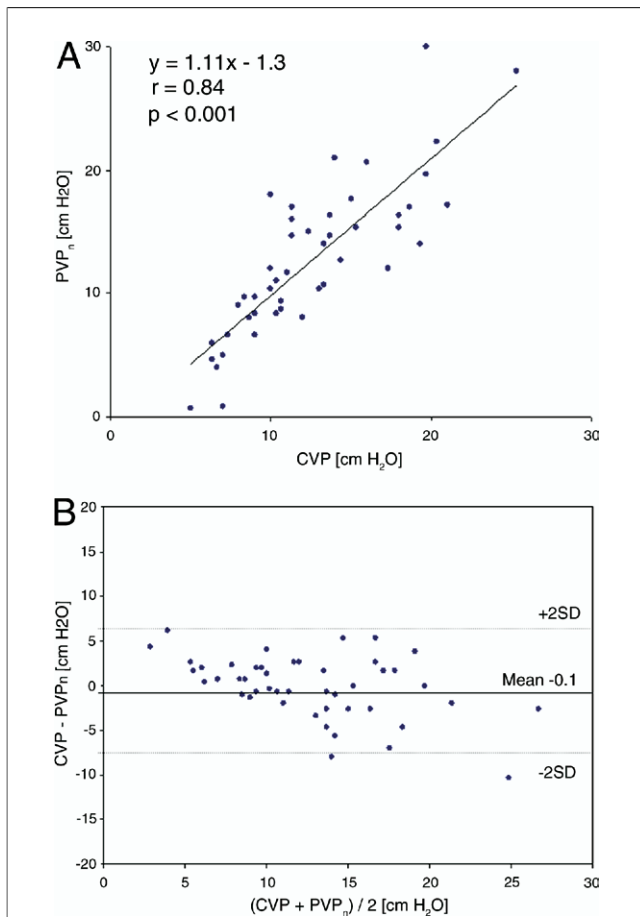
Figure 4 **Below Heart Level Measurements in ICU Patients**

(A) Linear regression: positive correlation between central venous pressure (CVP) and PVPn. **(B)** Bland-Altman plot: CVP and PVPn plotted against their mean. ICU = intensive care unit; other abbreviations as in Figure 2.
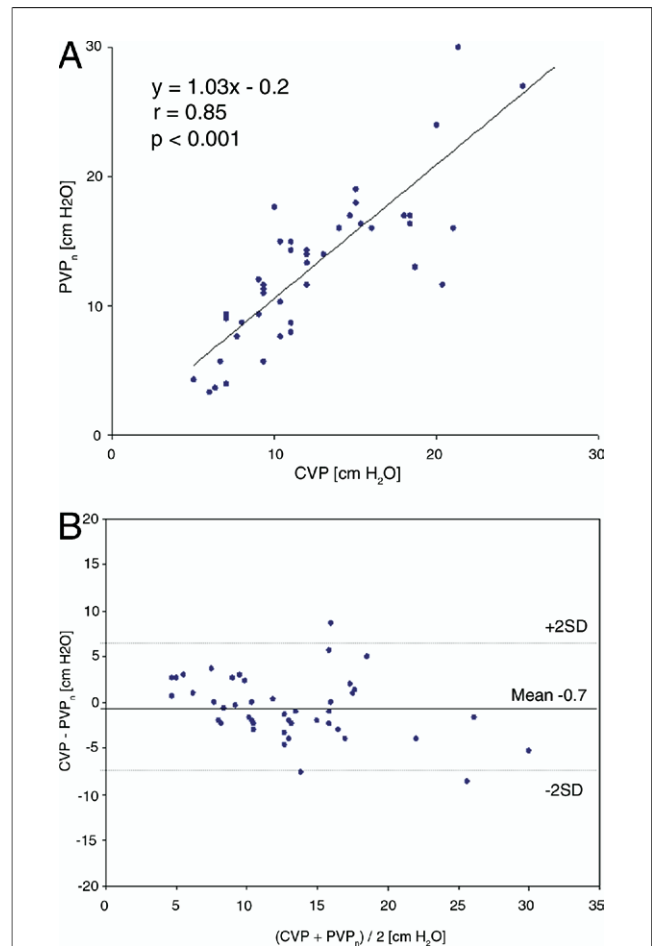

Figure 5 **Heart Level Measurements in ICU Patients**

(A) Linear regression: positive correlation between CVP and PVPn. **(B)** Bland-Altman plot: CVP and PVPn plotted against their mean. Abbreviations as in Figures 2 and 4.

Accuracy in predicting CVP by examination of the internal jugular vein in critically ill patients is poor. The correlation coefficient of bedside examination versus catheter values ranges from 0.65 to 0.74 with a moderate interobserver agreement (kappa statistics 0.30 to 0.65 [1]).

Recently published studies showed a good correlation between invasively measured PVP and CVP in different groups of patients under various conditions (3–5). The mean difference between CVP and PVPi in those studies ranged from −1.6 mm Hg up to −5 mm Hg, with a high degree of correlation ($r = 0.82$) in two studies (3,5). Our own work provides even stronger data, leading to our conclusion that at least in our setting, the noninvasive system measures CVP as accurately as with a central venous catheter.

The CVP measurement was reliable independent of the position of the forearm in relation to the level of the right atrium. Because elevation of the forearm is superfluous, measurement of CVP in clinical practice might be simpli-

Table 2 **Below Heart Level Measurements**

Patients	Mean Difference Between CVP and PVPn ± SD	Range	Spearman Correlation Coefficient r	Agreement*
1–29	−0.8 ± 4.1	−10.3 to 4.1	r=0.79	67%
30–50	0.7 ± 2.0	−2.7 to 6.2	r=0.93†	95%
All	−0.1 ± 3.5	−10.3 to 6.2	r=0.84	79%

*Clinically defined limit of agreement with a maximum difference of 4 cm H_2O. †p = 0.031 compared with patients 1 to 29.

CVP = central venous pressure; PVPn = noninvasive peripheral venous pressure.

Table 3 **Heart Level Measurements**

Patients	Mean Difference Between CVP and PVPn ± SD	Range	Spearman Correlation Coefficient r	Agreement*
1–29	−1.2 ± 3.8	−8.7 to 8.7	r=0.81	59%
30–50	0.1 ± 2.3	−3.3 to 2.3	r=0.89†	100%
All	−0.7 ± 3.4	−8.7 to 8.7	r=0.85	76%

*Clinically defined limit of agreement with a maximum difference of 4 cm H_2O. †p = 0.031 compared with patients 1 to 29.

CVP = central venous pressure; PVPn = noninvasive peripheral venous pressure.

fied. The level difference of the measuring point to the right atrium needs only to be subtracted from the pressure value measured at below heart level.

Study limitations. Seven patients had inadequate veins, not uncommon in critically ill patients as a result of multiple venous puncture, and were excluded, with a resultant preservation of feasibility in 86% of all screened patients.

The presence of a subclavian or central vein thrombosis could cause a false high peripheral measurement and must be considered in advance. Peripheral measurement may overestimate CVP, an underestimation of the CVP with the system, however, is unlikely. Therefore, a low or normal peripheral pressure is considered to exclude a clinically relevant elevated CVP.

The mean diameter of the examined vein in ICU patients was 2.2 mm, with the lowest diameter of only 0.5 mm, which was still accessible for examination, resulting in accurate measurement. Subcutaneous fatty tissue and depth of the vein under the skin may influence measurements in superficial veins. Our observation was that the selected vein was located in a depth of <10 mm in all subjects, and the quality of visualization of the vein was not dependent on the BMI. This was notably not only the case in the healthy population with a low normal BMI, but also in patients with a higher BMI.

Because of quality loss of the B-mode image through the silicone membrane, high-end ultrasound equipment is needed for adequate imaging of the vessel wall. A high-frequency ultrasound transducer to visualize superficial veins is essential and may not be available on every ICU. Technical advances, however, may provide portable ultrasound devices with adequate ultrasound transducers for emergency application (7).

Finally, measurements were made by 2 experienced vascular sonographers (C.T. and M.A.). This expertise notwithstanding, a learning curve effect emerged and was reflected in the 95% to 100% congruence rate of the investigators' data for the final 20 subjects. Training in our technique includes handling of the ultrasound system, optimizing imaging quality, selection of adequate vein segments, and obtaining experience to assess the point of collapse of the vein under examination. Although the learning curve phenomenon is well known during implementation of novel methodology, our experience in this regard was significant and underscores the necessity for method-specific training of medical personnel before use of our procedure.

Noninvasive measurement by controlled compression sonography may not be suitable for continuous monitoring of critically ill patients. It does, however, present an attractive alternative for assessment of emergency room patients when reliable estimation of CVP is desirable and an invasive technique is less than optimal.

Conclusions

A reliable noninvasive system for measuring PVP and CVP is presented. Controlled compression sonography is a valuable tool for measuring venous pressure in superficial peripheral veins and allows indirect measurement of CVP without the use of intravenous catheterization.

Reprint requests and correspondence: Dr. Christoph Thalhammer, University Hospital Basel, Petersgraben 4, CH-4031 Basel, Switzerland. E-mail: thalhammerc@uhbs.ch.

REFERENCES

1. McGee SR. Physical examination of venous pressure: a critical review. Am Heart J 1998;136:10–8.
2. Merrer J, De JB, Golliot F, et al. Complications of femoral and subclavian venous catheterization in critically ill patients: a randomized controlled trial. JAMA 2001;286:700–7.
3. Amar D, Melendez JA, Zhang H, Dobres C, Leung DH, Padilla RE. Correlation of peripheral venous pressure and central venous pressure in surgical patients. J Cardiothorac Vasc Anesth 2001;15:40–3.
4. Desjardins R, Denault AY, Belisle S, et al. Can peripheral venous pressure be interchangeable with central venous pressure in patients undergoing cardiac surgery? Intensive Care Med 2004;30:627–32.
5. Tobias JD, Johnson JO. Measurement of central venous pressure from a peripheral vein in infants and children. Pediatr Emerg Care 2003;19:428–30.
6. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–10.
7. Ziegler CM, Seitz K, Leicht-Biener U, Mauch M. Detection of therapeutically relevant diagnoses made by sonography of the upper abdomen: portable versus high-end sonographic units—a prospective study. Ultraschall Med 2004;25:428–32.