Noninvasive oscillometric cardiac output determination in the intensive care unit – comparison with invasive transpulmonary thermodilution

Alexander Reshetnik, Friederike Compton, Anna Schölzel, Markus Tölle, Walter Zidek & Markus van der Giet

Assessment of the cardiac output (CO) is usually performed with invasive techniques requiring specialized equipment in the intensive care unit (ICU). With TEL-O-GRAPH (TG), CO can be derived from the oscillometrically obtained brachial pulse wave during the measurement of brachial blood pressure. CO and stroke volume (SV) determinations with TG were compared with transpulmonary thermodilution measurements with the PICCO system (PICCO) in 38 haemodynamically unstable ICU patients with a total of 84 comparison measurements performed. SV (33.3 ± 9.0 ml/m² vs. 44.3 ± 14.4 ml/m², p < 0.001) and CO (2.7 ± 0.5 l/min/m² vs. 3.8 ± 1.2 l/min/m², p < 0.001) were underestimated significantly with TG and oscillometric brachial systolic blood pressure (BP) was significantly lower and diastolic BP significantly higher than invasive femoral artery pressure. A linear correlation was found between CO dimension and CO underestimation with TG. Correct tracking of CO changes with a fluid challenge was possible in 69.5% of measurements. Oscillometric noninvasive CO is possible in the ICU, but accuracy and precision of this new method are lacking. Implementation of a correction factor accounting for the linear increase in CO underestimation observed with increasing CO could improve CO assessment with TG in haemodynamically unstable patients.

Cardiac output (CO) is a major determinant of organ perfusion, and CO monitoring therefore an integral part of the care for haemodynamically compromised patients in the intensive care unit (ICU). Clinical gold standard for CO determination is intermittent thermodilution measurement either performed via a pulmonary artery catheter, or, less invasively, with the PICCO system using the transpulmonary approach with indicator detection in the systemic arterial circulation. Beat-to-beat CO monitoring is possible using CO calculation algorithms derived from the arterial pulse wave, and can either be performed invasively or noninvasively. To date, noninvasive pulse wave recordings have only been established for distal blood pressure measurement sites such as the finger (volume clamp technique) and the radial artery (applanation tonometry). Distal blood pressure, though, is known to underestimate central arterial pressure in haemodynamically compromised patients, and noninvasive pulse wave derivation is not always possible in patients on vasopressor therapy. With the Tel-O-GRAPH (TG) oscillometric brachial artery blood pressure measuring device, proximal noninvasive arterial pulse wave determination and CO estimation is possible, and the device has been evaluated clinically for the measurement of brachial blood pressure and calculation of central blood pressure and pulse wave velocity in haemodynamically stable patients. In the present study, we therefore compared noninvasive CO determination with TG with invasive thermodilution CO measurement in haemodynamically unstable ICU patients to evaluate whether oscillometric TG CO is suitable for use in the ICU.

Department of Nephrology and intensive care medicine, Charité Universitätsmedizin, Campus Benjamin Franklin, Hindenburgdamm 30, 12203, Berlin, Germany. Correspondence and requests for materials should be addressed to A.R. (email: alexander.reshetnik@charite.de)
Results

A total of 84 TG/PICCO comparison measurements were performed in 38 patients (Table 1). More than one comparison measurement was carried out in 31 patients, and in 33 instances measurements were performed before and immediately after a fluid challenge of 100 ml normal saline intravenously. Demographic data of the patients are displayed in Table 2. At time of study entry, 95 percent of patients were mechanically ventilated, and 76 percent were on continuous vasopressor support because of haemodynamic instability.

Mean cardiac index (CI) and stroke volume index (SVI) determined by noninvasive oscillometric TG calculation both were significantly and clinically relevantly lower than PICCO-CI and PICCO SVI measured with transpulmonary thermodilution (TG-CI 2.7 ± 0.5 l/min/m$^2$ vs. PICCO-CI 3.8 ± 1.2 l/min/m$^2$, p < 0.001 and TG-SVI 33.3 ± 9.0 ml/m$^2$ vs. PICCO-SVI 44.3 ± 14.4 ml/m$^2$, p = 0.001) (Table 3). Kolmogorov-Smirnov-Test revealed normal distribution for CI- and SVI- between-method bias. Bland-Altman analysis yielded a bias of 1.08 l/min/m$^2$ between noninvasive TG- and invasive PICCO-CI measurements, respectively (Fig. 1, panel A). Limits of agreement were ±1.96 l/min/m$^2$ with a percentage error of 68.3%. Differences between TG-CI and PICCO-CI increased in a linear fashion (slope = 1.14) with increasing CI as shown by the dashed line in the

| number of patients | number of measurements | number of measurements with fluid challenge$^a$ |
|--------------------|------------------------|-----------------------------------------------|
| single measurement | 7                      | 7                                             |
| single measurement on two separate days | 5 | 10                                      |
| two measurements before and after fluid challenge on the same day | 20 | 40 | 20 |
| two measurements before and after fluid challenge on two separate days | 4 | 16 | 8 |
| two measurements before and after fluid challenge on four separate days | 1 | 8 | 4 |
| two measurements before and after fluid challenge on day one, single measurement on day two | 1 | 3 | 1 |
| total | 38 | 84 | 33 |

Table 1. TG/PICCO comparison measurements (n = 84). $^a$fluid challenge: 100 ml normal saline intravenously.

| age, mean ± SD, years | 68.2 ± 12.3 |
| male gender, n (%) | 26 (68.4%) |
| body surface area, mean ± SD, m$^2$ | 1.9 ± 0.2 |
| body mass index mean ± SD, kg/m$^2$ | 26.4 ± 4.8 |
| arm circumference, mean ± SD, cm | 29.2 ± 4.3 |
| mortality, n (%) | 18 (47.4%) |
| at 28-days | 24 (63.2%) |
| at 3 month | 34 (89.5%) |
| SAPS on ICU admission, mean ± SD | 57.7 ± 20.6 |
| SOFA at study entry, mean ± SD | 11.2 ± 3.9 |
| mechanical ventilation, n (%) | 34 (89.5%) |
| on ICU admission | 34 (89.5%) |
| at study entry | 36 (94.7%) |
| vasopressor therapy at study entry, n (%) | 29 (76.4%) |
| acute kidney injury at study entry, n (%) | 28 (73.7%) |
| on renal replacement therapy | 23 (60.5%) |
| chronic illness, n (%) | 18 (47.4%) |
| hypertension | 17 (44.7%) |
| smoker | 7 (18.4%) |
| stroke | 10 (26.3%) |
| coronary heart disease | 10 (26.3%) |
| myocardial infarction | 8 (21.1%) |
| congestive heart failure | 7 (18.4%) |
| peripheral vascular disease | 5 (13.2%) |
| diabetes mellitus, insulin-dependent | 4 (10.5%) |
| diabetes mellitus, non-insulin-dependent | 10 (26.3%) |

Table 2. Patient characteristics (n = 38). SD = standard deviation, ICU = intensive care unit, SAPS = simplified acute physiology score, SOFA = sepsis-related organ failure score.
Comparison of haemodynamic parameters measured noninvasively with TEL-O-GRAPH (TG) and invasively with the PICCO system (PICCO). SD = standard deviation *Wilcoxon matched pairs test, *heart rate determined with electrocardiography monitoring and TG, respectively.

| parameter                      | PICCO mean ± SD | TG mean ± SD | p value* |
|-------------------------------|----------------|-------------|----------|
| heart rate, /min              | 86.9 ± 19.9    | 85.9 ± 19.8 | 0.72     |
| systolic blood pressure, mmHg | 123.6 ± 17.4   | 117.5 ± 16.0 | 0.006    |
| diastolic blood pressure, mmHg| 61.7 ± 10.7    | 70.6 ± 9.9  | <0.001   |
| cardiac output, l/min         | 7.34 ± 2.30    | 5.26 ± 0.93 | <0.001   |
| cardiac index, l/min/m²       | 3.80 ± 1.22    | 2.73 ± 0.50 | <0.001   |
| stroke volume, ml             | 85.2 ± 27.2    | 63.9 ± 16.3 | <0.001   |
| stroke volume index, ml/m²    | 44.3 ± 14.4    | 33.3 ± 9.0  | <0.001   |

Bland-Altman plot (Pearson’s r = 0.75). For SVI, bias was 11 ml/m² with limits of agreement of ±25.5 ml/m² (percentage error 65.7%).

Discussion

Our results show that noninvasive oscillometric brachial artery pulse wave acquisition with TG is feasible in haemodynamically unstable ICU patients. TG pulse wave analysis derived SV and CO, though, are clinically relevantly lower when compared to reference thermодilution measures with the PICCO system.

Different methods of pulse wave analysis can be used to calculate SV from the arterial pressure curve, depending on the underlying model of the circulation and the mathematical transformations performed[10, 11]. Systolic pulse contour analysis as used with TG is based on the Windkessel model, according to which SV is proportional to the area under the systolic portion of the pressure curve[12]. As with all other pulse wave analysis methods, individual aortic impedance has to be taken into account to calculate absolute SV and thus CO values based on this relationship. As opposed to calibrated pulse wave analysis methods, TG uses mathematical transformations only to determine aortic impedance[1]. When compared with calibrated pulse wave analysis, uncalibrated techniques have generally been shown to be less reliable and to underestimate CO especially in haemodynamically unstable patients with constantly changing vascular tone[3, 13–15]. This was recently confirmed in a meta-analysis of uncalibrated noninvasive CO monitoring devices used perioperatively[16].

With established uncalibrated CO determination devices, the pulse wave is usually obtained from a distal arterial site such as the radial artery or the finger[1]. Blood pressure measurements from peripheral arterial sites have been shown to systematically underestimate central arterial pressure during haemodynamic instability, which in turn influences accuracy and precision of pulse wave derived CO[13, 14, 17]. Reliable blood pressure determination has been shown to be possible with TG in haemodynamically stable ambulatory patients when compared to sphygmomanometric auscultatory blood pressure readings, and oscillometric brachial blood pressure determination is routinely used both in the ICU and the operating theatre even though reliability has not been proven for adult patients in systematic precision and accuracy studies[4, 18–20]. Our data show that despite the more proximal arterial site systolic blood pressure is also underestimated with TG in haemodynamically compromised patients when compared to invasive femoral arterial pressure measurement. Diastolic blood pressure, on the other hand, is overestimated, yielding a deformed pulse wave with diminished pulse pressure used to calculate SV and CO.

To our knowledge, there are only two other studies evaluating the performance of oscillometry-based SV and CO calculation. Liu and coworkers compared oscillometrically derived SV with echocardiographic measurements in 55 haemodynamically stable patients undergoing routine cardiac disease diagnosis[8]. Using a different pulse contour analysis algorithm, the authors found a strong correlation and only minor differences between oscillometry-based and echocardiography-derived SV. Oscillometric SV calculation was evaluated in ten ICU patients in the other study and compared to pulmonary artery thermodilution measurements[3]. Precision and accuracy were reported to be 0.25 ± 12.5 ml (as compared to 21.2 ± 25.1 ml in our study, data not shown), but it was not stated whether TG-SV was higher or lower than thermodilution SV, and only limited data was provided concerning the haemodynamic status of the study subjects. Both studies reported better accuracy of the oscillometric devices that we could show. A possible explanation could be an amount of haemodynamic instability in our patients, which can decrease the sensitivity of peripheral sensors. Thus, final CO/SV calculation can become erroneous.

Bland-Altman analysis of SV and CO data in our study revealed that there was a linear correlation between the dimension of SV and CO, respectively, and the magnitude of underestimation by TG: The higher SV and CO were, the larger the difference between TG and PICCO measurements became. A similar phenomenon had been found in an earlier study performed at our institution comparing applanation tonometry-derived CO and...
pulmonary artery thermodilution measurements. Because of the linearity of this error it might be possible to develop a correction factor that could be implemented in the TG-CO calculation algorithm allowing for a more precise CO estimation with TG in patients with higher CO levels.

Clinically more important than single absolute CO values often are relative CO changes in response to a therapeutic intervention. CO trending abilities can be assessed using different methods, of which visualization with a 4-quadrant plot and reporting of concordance rates is a method frequently used. We evaluated CO changes with a fluid challenge and found that TG failed to reliably trend CO changes with a concordance rate of 69.5% between TG- and PICCO-ΔCI, which was below an acceptable level of 90–95%. In consistence with the low concordance, 4-quadrant plot visualized low trending ability with a relevant rate of discordant measurements, poor correlation index (r = 0.15) and wide distribution of data points around the 45° diagonal, which represents equal numerical values revealed by TG and PICCO. To our knowledge, there are no other studies assessing the ability of non-invasive oscillometric devices to track CO changes. Several studies addressed this issue for other techniques such as arterial pulse contour cardiac output monitoring systems, transtracheal Doppler, thoracic electric bioimpedance monitoring, transesophageal Doppler with different findings. In general, arterial pulse contour based CO analysis was shown to track CO changes with poor reliability comparable to our results. However, it lacks the clearly defined numeric values, which could be used for comparisons between studies, and for the definition of good, acceptable, and poor agreement.

We showed clinically relevant differences in absolute CO values calculated with TG compared to thermodilution measurements. This could be an important factor explaining the poor ability to track CO changes by the

Figure 1. (A) Agreement between invasive PICCO measured cardiac index (PICCO-CI) and noninvasive TEL-O-GRAPH derived cardiac index (TG-CI): bias 1.08 l/min/m², limits of agreement −1.15 to 3.31 l/min/m² (percentage error 68.3%), dashed line represents the linear correlation between absolute CI level and PICCO- and TG-CI differences (Pearson’s r = 0.75); (B) Agreement between invasive PICCO measured stroke volume index (PICCO-SVI) and noninvasive TEL-O-GRAPH derived stroke volume index (TG-SVI): bias 11 ml/m², limits of agreement −14.5 to 36.5 ml/m² (percentage error 65.7%), dashed line represents the linear correlation between absolute SVI level and PICCO- and TG-SVI differences (Pearson’s r = 0.49).
Figure 2. Comparison of mean systolic blood pressure (A) and diastolic blood pressure (B) measured with the PICCO-system (PICCO) and TEL-O-GRAPH (TG); *-Wilcoxon matched pairs test.

Figure 3. 4-quadrant plot of TEL-O-GRAPH (TG) derived cardiac index change (ΔCI) after a fluid challenge of 100 ml normal saline intravenously compared with PICCO measured ΔCI (concordance rate = 69.5%). Points with equal numerical values are located on the 45° diagonal within the quadrant (the dotted line). Exclusion zone is marked by grey rectangle.
tested device. Future studies should be able to show whether improvement in agreement of CO assessment would also improve the ability to track CO changes.

We acknowledge several limitations of our study. Our study group was relatively small, and in most patients more than one measurement was performed and analyzed. Most, but not all patients were on vasopressor support during study measurements. As with all studies comparing two physiologic methods, bias does not necessarily only arise on the part of the method evaluated, but can also be due to inaccuracies of the reference method. Transpulmonary thermodilution CO measurement has been shown to be a reliable method in numerous studies, but the clinical gold standard it was compared with—pulmonary artery thermodilution—likewise has inherent inaccuracies and limitations. The character of our study was observational, and apart from the standardized fluid challenge performed when clinically indicated, no intervention was carried out for study purposes. Confounding factors such as positive end-expiratory pressure on mechanical ventilation were therefore not controlled, and the study population was rather heterogeneous. Our study is a method-comparison study of non-invasive CO assessment vs. invasive thermodilution CO measurement as a clinical “gold standard”. Invasive CO monitoring was performed because of the critical illness of our patients. Thus, the findings obtained in our study are limited to this group of critically ill and haemodynamically unstable patients and cannot readily be transferred to other less ill patient collectives.

Despite these limitations, we were able to show that noninvasive oscillometric CO determination is feasible in the ICU. TG does not require specialized equipment as with applanation tonometry or finger blood pressure measurement, and the pulse wave is derived more proximally than with those techniques. With TG, CO can be determined at the same time as the blood pressure is taken, and blood pressure measurement is performed with a method well established in patient monitoring. Future studies will have to show if modifications in the calculation algorithm like the introduction of a correction factor for increasing CO values can improve the performance of oscillometric pulse wave analysis and CO determination.

In conclusion, our study shows that oscillometry-based CO determination is generally possible in haemodynamically unstable ICU patients. Even though precision and accuracy of CO estimation with TG were not sufficient, we were able to demonstrate a linear correlation between the dimension of CO and its underestimation with TG pulse wave analysis. A correction of this systematic error could increase CO determination accuracy significantly, so that oscillometry-derived CO estimation could potentially become an alternative to other more complex noninvasive CO determination methods in the ICU.

Methods
The study was approved by the Charité Universitätsmedizin Berlin regional research ethics committee (ref: EA1/184/15). All methods were performed in accordance with the relevant guidelines and regulations. Informed consent was obtained from the patient or their legal representative, respectively, before enrollment in the study.

A total of 38 patients treated in the medical ICU of the Charité Campus Benjamin Franklin University hospital in Berlin, Germany between June 2015 and June 2016 and monitored with a PICCO system (Pulsion Medical Systems, Feldkirchen, Germany) as part of their clinical treatment were prospectively enrolled in the study. Exclusion criteria were age below 18 years, pregnancy, known aortic valve, aortic arch, axillary or brachial artery stenosis, as well as cardiac arrhythmias precluding noninvasive calculation of haemodynamic parameters by the TG blood pressure monitoring device. Patients were categorized as haemodynamically unstable if mean arterial pressure (MAP) was <65 mmHg or vasopressor therapy was necessary to maintain MAP ≥65 mmHg. The TG device used in the study was kindly provided by I.E.M., Stolberg, Germany. With TG brachial blood pressure is determined oscillometrically with a conventional brachial blood pressure cuff, and the arterial pulse wave is derived using a high fidelity pressure sensor with the cuff inflated at the diastolic blood pressure level for ten seconds. Estimation of left ventricular stroke volume (SV) and CO is achieved by a series of mathematical transformations of the brachial pulse wave described in detail elsewhere. Briefly, the aortic pressure waveform is calculated using generalized transfer functions (Fourier analysis and de-compensation into wave harmonics), and the aortic flow curve by the means of an adopted, multidimensional Windkessel model. SV is then derived from the time lag between pressure and flow curves, generally referred to as the “characteristic impedance (Zc)”. CO is calculated by multiplying SV with the heart rate also derived from the arterial pulse wave.

With the PICCO system, CO was determined using transpulmonary thermodilution. A bolus of 20 mL of cold (0–6°C) normal saline solution was manually injected (injection time ≤10 seconds) into the distal lumen of a central venous catheter and detected in the systemic circulation by a thermistor-tipped femoral artery catheter (Pulsiocath PV2015L20, Pulsion Medical Systems, Feldkirchen, Germany). CO was calculated as the mean value of three consecutive measurements. To obtain SV, CO was divided by the heart rate determined with electrocardiography (ECG) monitoring.

Noninvasive SV (TG-SV) and CO (TG-CO) were determined at the time of invasive PiCCO CO (PiCCO-CO) and SV (PiCCO-SV) measurements. For TG measurements, blood pressure cuff size was chosen according to the manufacturer’s specifications (cuff sizes for arm circumferences of 24–34 cm and 32–42 cm, respectively – for arm circumference between 32 and 34 cm the smaller cuff was used). If possible, measurements were performed on both the left and the right arm, and TG-SV and TG-CO calculated as the mean of three (unilateral) or six (bilateral) measurements, respectively.

CO and SV results were indexed to body surface area, and are referred to as cardiac index (CI) and stroke volume index (SVI), respectively. At the time of measurements, blood pressures determined both noninvasively with TG at the brachial artery and invasively with the PiCCO system in the external iliac artery were recorded as well as heart rate determined with TG and ICU ECG monitoring, respectively. Patient population characteristics and severity of illness scores (simplified acute physiology score, SAPS, and sepsis-related organ failure assessment score, SOFA) were also registered.
Data were analyzed using Graph-Pad Prism 5 (GraphPad Software, La Jolla, CA, USA) and SPSS Statistics 23.0 (IBM, New York, NY, USA). Results are expressed as mean ± standard deviation. Statistical differences between paired measurements were assessed using nonparametric Wilcoxon testing, and a two-sided p value of <0.05 was considered statistically significant. For agreement between invasive TG-CI / TG-SVI and noninvasive CO, the recommended margin for the exclusion zone in a 4-quadrant plot is 0.5 l/min. To compare CI changes, the exclusion zone was defined by dividing 0.5 l/min by mean body surface area.

References

1. Peeters, Y. et al. Haemodynamic monitoring: To calibrate or not to calibrate? Part I - Calibrated techniques. *Anaesthesia intensive therapy*, doi:10.5603/AITA.2015.0073 (2015).
2. Teboul, J. L. et al. Less invasive haemodynamic monitoring in critically ill patients. *Intensive Care Med* 42, 1350–1359, doi:10.1007/s00134-016-4375-7 (2016).
3. Bernards, J. et al. Haemodynamic monitoring: To calibrate or not to calibrate? Part 2 - Non-calibrated techniques. *Anaesthesia intensive therapy*, doi:10.5603/AITA.2015.0076 (2015).
4. Amedoot, K., Palmers, P. J. & Malbrain, M. L. The accuracy of noninvasive cardiac output and pressure measurements with finger cuff: a concave review. *Current opinion in critical care* 21, 232–239, doi:10.1097/MCC.0000000000000198 (2015).
5. Wagner, J. V. et al. Autocalibrating pulse contour analysis based on radial artery applanation tonometry for continuous non-invasive cardiac output monitoring in intensive care unit patients after major gastrointestinal surgery—a prospective method comparison study. *Anaesthesia and intensive care* 44, 340–345 (2016).
6. Dorman, T. et al. Radial artery pressure monitoring underestimates central arterial pressure during vasopressor therapy in critically ill surgical patients. *Critical care medicine* 26, 1646–1649 (1998).
7. Wasserteiner, S., Mayer, C. & Breitenecker, F. Modeling arterial and left ventricular coupling for non-invasive measurements. *Simulation Modelling Practice and Theory* 16, 988–997 (2008).
8. Reshetnik, A., Gohlisch, C., Zidek, W., Tolle, M. & van der Giet, M. Central blood pressure assessment using oscillometry is feasible and accurate. *Br J Anaesth* 113, 452–479, doi:10.1016/s0007-0912(14)60315-3 (2014).
9. de Wilde, R. B., Schreuder, J. J., van den Berg, P. C. & Jansen, J. R. An evaluation of cardiac output by five arterial pulse contour techniques during cardiac surgery. *Anaesthesia* 62, 760–768, doi:10.1111/j.1365-2044.2007.05135.x (2007).
10. Jansen, J. R., Wesseling, K. H., Settels, J. J. & Schreuder, J. J. Continuous cardiac output monitoring by pulse contour during cardiac surgery. *Eur Heart J (Suppl I)*, 26–32 (1990).
11. Compton, F. D., Zuidstra, G., Hoffmann, C., Zidek, W. & Schafer, J. H. Performance of a minimally invasive uncalibrated cardiac output monitoring system (FloTrac/Vigileo) in haemodynamically unstable patients. *Br J Anaesth* 100, 451–456, doi:10.1093/bja/aem409 (2008).
12. Compton, F. et al. Noninvasive cardiac output determination using applanation tonometry-derived radial artery pulse contour analysis in critically ill patients. *Anesthesiology and analgesia* 106, 171–174, table of contents, doi:10.1213/ane.0b013e3181d5e05e (2008).
13. Peyton, P. J. & Chong, S. W. Minimally invasive measurement of cardiac output during surgery and critical care: a meta-analysis of accuracy and precision. *Anaesthesia* 113, 1220–1235, doi:10.1093/ALN.00183181818484 (2010).
14. Joosten, A. et al. Accuracy and precision of non-invasive cardiac output monitoring devices in perioperative medicine: a systematic review and meta-analysisiddagger. *Br J Anaesthesia* 114, 298–310, doi:10.1093/bja/aew461 (2015).
15. Camporota, L. & Beale, R. Pitfalls in haemodynamic monitoring based on the arterial pressure waveform. *Critical care medicine* 12, 124, doi:10.1186/cc845 (2010).
16. Lakhll, K. et al. Tracking hypotension and dynamic changes in arterial blood pressure with brachial cuff measurements. *Anesthesia and analgesia* 109, 494–501, doi:10.1213/ane.0b013e3181ba8d8a (2009).
17. Lakhll, K., Macq, C., Ehrmann, S., Boulain, T. & Capdevila, X. Noninvasive monitoring of blood pressure in the critically ill: reliability according to the cuff site (arm, thigh, or ankle). *Critical care medicine* 40, 1207–1213, doi:10.1097/CCM.0b013e3182328ad42 (2012).
18. Chatterjee, A., DePriest, K., Blair, R., Bowton, D. & Chin, R. Results of a survey of blood pressure monitoring by intensivists in critically ill patients: a preliminary study. *Critical care medicine* 38, 2335–2338, doi:10.1097/CCM.0b013e3181fa577f (2010).
19. Liu, S. H., Lin, T. H., Cheng, D. C. & Wang, J. J. Assessment of Stroke Volume From Brachial Blood Pressure Using Arterial Pressure Waveform Analysis and the concordance rate determined41. For CO, the recommended margin for the exclusion zone in a 4-quadrant
20. Breukers, R. M., Seepkshrouy, S., Spiegeleen, S. R. & Groeneveld, A. B. Cardiac output measured by a new arterial pressure waveform analysis method without calibration compared with thermodilution after cardiac surgery. *Journal of cardiothoracic and vascular anesthesia* 21, 632–635, doi:10.1053/j.jvca.2007.01.001 (2007).
30. Perrino, A. C. Jr., O‘Connor, T. & Luther, M. Transtracheal Doppler cardiac output monitoring: comparison to thermodilution during noncardiac surgery. *Anesthesia and analgesia* 78, 1060–1066 (1994).
31. Shoemaker, W. C. *et al.* Multicenter trial of a new thoracic electrical bioimpedance device for cardiac output estimation. *Critical care medicine* 22, 1907–1912 (1994).
32. Parra, V. *et al.* Transoesophageal echocardiography accurately detects cardiac output variation: a prospective comparison with thermodilution in cardiac surgery. *Eur J Anaesthesiol* 25, 135–143, doi:10.1017/S0265021507001354 (2008).
33. Lafanechere, A. *et al.* Cardiac output measurement during infrarenal aortic surgery: echo-esophageal Doppler versus thermodilution catheter. *Journal of cardiothoracic and vascular anesthesia* 20, 26–30, doi:10.1053/j.jvca.2005.07.029 (2006).
34. Critchley, L. A. & Critchley, J. A. A meta-analysis of studies using bias and precision statistics to compare cardiac output measurement techniques. *Journal of clinical monitoring and computing* 15, 85–91 (1999).
35. Sakka, S. G., Reinhart, K. & Meier-Hellmann, A. Comparison of pulmonary artery and arterial thermodilution cardiac output in critically ill patients. *Intensive Care Med* 25, 843–846 (1999).
36. Holm, C., Melcer, B., Horbrand, F., Henckel von Donnersmarck, G. & Muhlbauer, W. Arterial thermodilution: an alternative to pulmonary artery catheter for cardiac output assessment in burn patients. *Burns: journal of the International Society for Burn Injuries* 27, 161–166 (2001).
37. Gust, R. *et al.* Cardiac output measurement by transpulmonary versus conventional thermodilution technique in intensive care patients after coronary artery bypass grafting. *Journal of cardiothoracic and vascular anesthesia* 12, 519–522 (1998).
38. Nishikawa, T. & Dohi, S. Errors in the measurement of cardiac output by thermodilution. *Canadian journal of anaesthesia=Journal canadien d’anesthésie* 40, 142–153, doi:10.1007/BF03011312 (1993).
39. Saugel, B. *et al.* The T-Line TL-200 system for continuous non-invasive blood pressure measurement in medical intensive care unit patients. *Intensive Care Med* 38, 1471–1477, doi:10.1007/s00134-012-2617-x (2012).
40. Bogert, L. W. & van Lieshout, J. J. Non-invasive pulsatile arterial pressure and stroke volume changes from the human finger. *Experimental physiology* 90, 437–446, doi:10.1113/expphysiol.2005.030262 (2005).
41. Critchley, L. A., Lee, A. & Ho, A. M. A critical review of the ability of continuous cardiac output monitors to measure trends in cardiac output. *Anesthesia and analgesia* 111, 1180–1192, doi:10.1213/ANE.0b013e3181f0a5b (2010).

**Acknowledgements**

TG devices were provided by the manufacturer of the device. This work was not supported by any funding.

**Author Contributions**

A.R.: conception and design of the article, drafting the article; final approval of the version to be published; accountable for all aspects of the work. F.C.: analysis and interpretation of data, drafting the article; final approval of the version to be published; accountable for all aspects of the work. A.S.: acquisition of data, drafting the article; final approval of the version to be published; accountable for all aspects of the work. M.T.: analysis and interpretation of data, revising the article for important intellectual content; final approval of the version to be published; accountable for all aspects of the work. W.Z.: analysis and interpretation of data, revising the article for important intellectual content; final approval of the version to be published; accountable for all aspects of the work. M.G.: analysis and interpretation of data, revising the article for important intellectual content; final approval of the version to be published; accountable for all aspects of the work.

**Competing Interests:** The authors declare that they have no competing interests.

**Publisher’s note:** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

[Open Access] This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit [http://creativecommons.org/licenses/by/4.0/](http://creativecommons.org/licenses/by/4.0/).

© The Author(s) 2017