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Accuracy of oscillometric blood pressure measurement in critically ill neonates with reference to the arterial pressure wave shape

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Abstract *Objective:* To perform further evaluation of the oscillometric device for neonatal arterial blood pressure (ABP) measurement, using a catheter-manometer system (CMS) for accurate intraarterial measurement. We aimed to describe the influence of the radial artery wave shape on oscillometric ABP determination, as pressure wave-shape influences the relationships between systolic arterial pressure (SAP), diastolic arterial pressure (DAP) and mean arterial pressure (MAP) in the wave. These relationships are part of the algorithms contributing to the final ABP determination in the oscillometric device.
Design: Intra-patient comparison of two blood pressure measurement systems.
Setting: Neonatal intensive care unit.
Patients: In 51 critically ill newborn infants, ABP was determined oscillometrically in the brachial artery and, simultaneously, invasively in the radial artery using a high-fidelity CMS. Clinical data of the infants were: gestational age: 29 (25–41) weeks; birthweight: 1200 (500–3675) g, postnatal age: 6 (2–46) h.
Methods: Statistical analysis was performed with the paired Student's *t*-test. Multiple regression analysis was used to determine the influence of birthweight and height of the blood pressure on the results.
Measurements and main results: In 51 infants, 255 paired values of SAP, DAP and MAP were recorded. In all recordings, we determined the relationship between SAP, DAP and MAP, using the equation:
$MAP = \alpha\%(SAP - DAP) + DAP$.
For SAP, DAP, MAP and α, we computed mean differences (bias) and the limits of agreement (precision). Biases for SAP, DAP, MAP and α were significantly different from zero ($P < 0.001$) and the limits of agreement for SAP, DAP and MAP were wide: 18.8 mmHg, 17.2 mmHg and 15.2 mmHg respectively. The relationship between invasive and noninvasive values is only partly (7–19%) influenced by the height of the blood pressure; low values of SAP, DAP and MAP tend to give overestimated oscillometric values. In the relationship between SAP, DAP and MAP, α was found to be 47% invasively (as generally found in the radial artery in newborns) and 34% noninvasively (as generally found in the brachial/radial artery in adults).

Conclusions: Inaccuracy of the oscillometric device may be partly explained by the incorporation of an inappropriately fixed algorithm for final ABP determination in newborns. Care should be taken when interpreting the oscillometrically derived values in critically ill newborn infants.

Key words Blood pressure measurement · Radial artery pressure · Wave form · Oscillometry · Newborn infant · Intensive care

Abbreviations *ABP* Arterial blood pressure · *SAP* Systolic arterial pressure · MAP Mean arterial pressure · *DAP* Diastolic arterial pressure · *PP* Pulse pressure · *MAP%* Level of MAP in the wave in relation to SAP and DAP, expressed as: MAP% = (MAP − DAP)/(SAP − DAP) × 100% · *CMS* Catheter-manometer system · *IRDS* Idiopathic respiratory distress syndrome

Introduction

Arterial blood pressure (ABP) monitoring is an integral part of neonatal intensive care. Direct arterial pressure monitoring has been generally accepted as the gold standard for ABP measurement on the condition that the requirements for dynamic performance of the measurement system have been fulfilled [1–4]. Dynamic performance depends upon the composition of the CMS and upon the properties of the different components and can be degraded by air bubbles in the system fluid [5–8]. Since the requirements for good dynamic performance for neonatal use are high, accurate blood pressure measurements often cannot be obtained [7, 9]. Recently, a new technique enabling accurate pressure measurement through radial artery catheters in newborns has become available [10]. Using this high-fidelity CMS, we studied radial artery pressure wave forms and found evidence that these wave forms resemble aortic wave forms [11] (Fig. 1). As the mean pressure of the wave depends upon the pressure wave contour [12, 13], the relationship between SAP, DAP and MAP in neonatal radial artery waves is different from that found in peripheral arteries in adults. In the neonatal radial artery wave, MAP can be approximated by the equation MAP = 50%(SAP − DAP) + DAP, which differs from the equation holding for adult brachial/radial artery waves [14].

As an alternative for invasive ABP measurement, noninvasive oscillometric ABP measurement techniques are currently widely employed. Much research has been done to assess the accuracy of oscillometric measurement techniques in the newborn [15–23]. However, these studies were performed with various methods and materials and often with a lack of data on the dynamic performance of the CMS and, therefore, conclusions were in part conflicting. On the basis of more accurate invasive pressure measurement and knowledge of the pressure wave form, further evaluation of the oscillometric device has become possible.

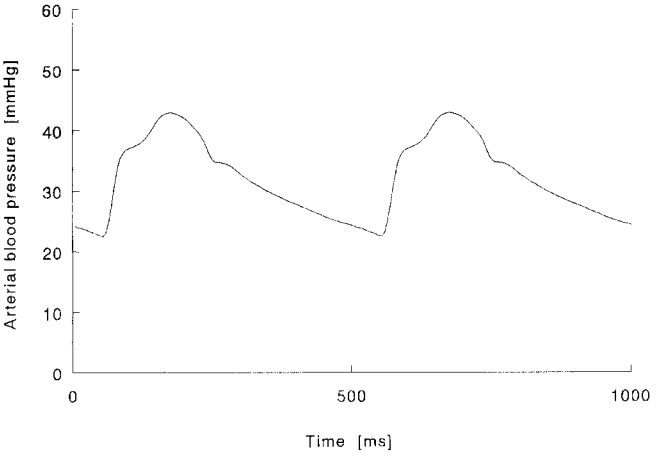

Fig. 1 Representative example of a radial artery pressure wave in the newborn infant

This study was designed to assess agreement between the invasive and the oscillometric methods regarding measurement of SAP, DAP and MAP in the upper limb, and to determine the influence of the pressure wave shape on ABP determination with the oscillometric device.

Patients and methods

Patients

Fifty-one newborn infants admitted for intensive care and requiring indwelling arterial cannulation as part of their care were studied. In these infants, 255 simultaneous invasive and noninvasive recordings were performed.

All infants were cannulated in either the left or the right radial artery, as peripheral artery cannulation is standard practice in our intensive care unit. The clinical characteristics of the infants were: median gestational age: 29 (range 25–41) weeks; median birthweight: 1200 (range 500–3675) g and median postnatal age 6 (range 2–46) h. All infants suffered from respiratory insufficiency on admission. The diagnosis was idiopathic respiratory distress syndrome (IRDS) in 27 infants, pneumonia in 12 infants, IRDS + pneumonia in 4 infants, asphyxia in 5 infants and wet lung in 2 infants. All patients

were mechanically ventilated. None of the infants received vasoactive agents.

This study was approved by the Ethical Committee of our hospital and informed parental consent was obtained.

Materials and methods

Oscillometric blood pressure measurement was performed using the Hewlett Packard Merlin monitor (HP M1166A, model 66S, noninvasive pressure module HP M1008B). A blood pressure cuff (HP M1868A) was applied, using the appropriate size for each infant based on the limb circumference according to the recommendations of the manufacturer. Accurate invasive blood pressure measurement was performed using a high-fidelity CMS, consisting of a 24-gauge teflon catheter (Neoflon, length: 16 mm, Viggo-Spectramed), connected to a transparent threeway stopcock (Viggo-Spectramed). A side-hole tip-transducer was sealed in a Luer-Lock connector to another end of the stopcock. In a previous study, this system was shown to have a uniform frequency response ($\pm$ 3 dB) up to at least 50 Hz (damped natural frequency: 95 Hz; damping coefficient: 0.15) [10]. The CMS was connected to a physiological monitor (HP 78834A, Andover, Mass.) to amplify the signal. In this monitor, MAP is determined by calculating the area under the pressure wave form averaged over the cardiac cycle. Displayed blood pressure values are averaged over eight wave forms [24].

Preparation and performance of the pressure measurements were the following. After left or right radial artery cannulation, the catheter was connected to the high-fidelity CMS, while care was taken to avoid the introduction of air bubbles. In order to avoid blood clotting, continuous flushing with a heparinized solution (1 U Hep/ml) was performed at a rate of 0.6 –1.0 ml/h. At the time of our studies, flushing was discontinued and the system was calibrated against free air. Oscillometric measurements were performed in the brachial artery in the opposite arm and were carried out according to the manufacturers' recommendations. In each patient, five consecutive measurements were taken with a pause of at least 30 s between each measurement. At the end of the cuff-deflation period, immediately after appearance of the noninvasive value on the monitor, simultaneous readings of both invasive and noninvasive SAP, DAP and MAP were performed. During the study, all infants were in a supine position and quiet and both arms were straightened at the elbow. Recordings were repeated if arm movements were noted during the period of oscillometric recording.

Data analysis

A total of 255 paired values of invasive and noninvasive determined SAP, DAP and MAP was found. Agreement between the methods was assessed by calculating differences between paired values of SAP (ΔSAP), DAP (ΔDAP), and MAP (ΔMAP), as found by the two techniques (noninvasive value minus invasive value). Results are reported according to Bland and Altman [25]. The means of these differences (bias) and the limits of agreement (precision) were determined. These limits of agreement are intervals for individual oscillometric measurements to predict the intra-arterial value. To find these limits, we determined for each parameter the range in which 95% of the differences were expected to be, using the equations for normal (Gaussian) distributions, i.e. between $\Delta + 1.96$ SD and $\Delta - 1.96$ SD. The agreement plots (Figs. 3a–d) show differences between the methods on the Y-axis and the intra-arterial value on the X-axis. To test the hypothesis that for each parameter the bias was zero, we used the paired t-test. To assess the precision of the obtained mean differences between the methods, we determined the

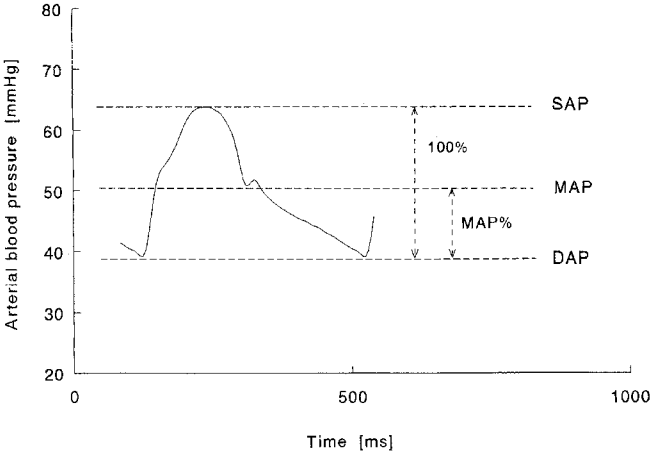

Fig. 2 Relationship between systolic (SAP), diastolic (DAP) and mean arterial pressure (MAP) in the radial artery wave in the newborn. The position of the MAP in the wave in relation to SAP and DAP is: (MAP-DAP)/(SAP-DAP) $\times$ 100%. This parameter is referred to as MAP%

95 % confidence interval (CI) for the mean difference of each parameter. To determine the relationship between SAP, DAP and MAP in both methods, MAP was expressed in parameters of SAP and DAP in each recording using the following equation: $MAP = \alpha\%(SAP - DAP) + DAP$ i.e. $\alpha = (MAP - DAP)/(SAP - DAP) \times 100\%$. This parameter α%, which describes the position of MAP in the wave in relation to SAP and DAP, is referred to here, as in earlier studies [14], as MAP%. (Fig. 2). Thus, 255 paired values of MAP% were found. For these paired values of MAP%, we also determined the mean differences with the 95% CI, the significance of the difference and the limits of agreement.

In addition, we focused on the influence of birthweight and blood pressure (systolic, diastolic and mean pressure) on the relationship between invasive and noninvasive blood pressure measurement. Multiple regression analysis was performed to analyze the influence of birthweight and blood pressure on the results. The following equations were used: (1) $\Delta SAP = \alpha + \beta SAP_{inv} + \gamma BW + \delta SAP_{inv}BW$ (2) $\Delta MAP = \alpha + \beta MAP_{inv} + \gamma BW + \delta MAP_{inv}BW$ (3) $\Delta DAP = \alpha + \beta DAP_{inv} + \gamma BW + \delta DAP_{inv}BW$

Results

Blood pressure values as found invasively and oscillometrically are shown in Table 1. Biases (noninvasive minus invasive values) with standard deviations, the 95% CI for precision of the biases and the limits of agreement for SAP, DAP, MAP and MAP% are shown in Table 2. The biases are: ΔSAP = 1.5 mmHg, ΔDAP = $-$ 1.0 mmHg, ΔMAP = $-$ 2.3 mmHg and ΔMAP% = $-$ 12.3%. All biases were significantly different from zero ($P < 0.001$) . It is notable that the differences in MAP% that were measured noninvasively tended to give a lower value (between $-$ 12.9 and $-$ 11.7%). These differences between the two methods are plotted against the intra-arterial value

Table 1 Noninvasive and invasive blood pressure values simultaneously recorded. Values are mean and SD. *SAP* systolic arterial pressure, *DAP* diastolic arterial pressure, *MAP* mean arterial pressure, *MAP*% (MAP − DAP)/(SAP − DAP) × 100%

	Invasive	Noninvasive
SAP (mmHg)	47.2 ± 7.2	48.7 ± 6.7
DAP (mmHg)	29.6 ± 6.2	28.5 ± 6.6
MAP (mmHg)	37.8 ± 6.4	35.5 ± 6.1
MAP% (%)	46.8 ± 3.9	34.4 ± 3.6

Table 2 Differences (bias), 95% confidence interval and 95% limits of agreement between invasively and noninvasively simultaneously recorded blood pressure data. (Values are mean and SD for the bias and range for the 95% confidence interval and for the 95% limits of agreement. *CI* confidence interval, *SAP* systolic arterial pressure, *DAP* diastolic arterial pressure, *MAP* mean arterial pressure, *MAP*% (MAP-DAP)/(SAP-DAP) × 100%)

	Bias	95%CI	agreement
SAP (mmHg)	1.5 ± 4.8*	0.9 to 2.1	−7.9 to 10.9
DAP (mmHg)	−1.0 ± 4.4*	−1.6 to −0.4	−9.6 to 7.6
MAP (mmHg)	−2.3 ± 3.9*	−2.7 to −1.9	−9.9 to 5.3
MAP% (%)	−12.3 ± 5.4*	−12.9 to −11.7	−23.0 to −1.8

* Bias is significant different from zero ($P < 0.001$)

in Fig. 3a–d according to Bland and Altman [25]. These figures also show the limits of agreement (notice the range of oscillometric values corresponding to an individual intra-arterial value in each figure; note also that both limits of agreement are below zero in determination of MAP%.)

The influence of birthweight and blood pressure height on agreement between invasive and noninvasive pressure measurement was as follows:

Eq. (1): $\beta < 0.001$ ($r^2 = 19\%$), γ = NS, δ = NS

Eq. (2): $\beta < 0.001$ ($r^2 = 16\%$), γ = NS, δ = NS

Eq. (3): $\beta < 0.001$ ($r^2 = 7\%$), γ = NS, $\delta = 0.02$ $r^2 = 0.6\%$)

As can be seen, Δ SAP, Δ MAP and Δ DAP are influenced by the invasive SAP, MAP and DAP: the higher the SAP_{inv}, MAP_{inv} and DAP_{inv}, the less the oscillometric overestimation of SAP, MAP and DAP; underestimation also frequently occurs in the higher blood pressure ranges of SAP, MAP and DAP. However, despite this statistically significant slope, the low values of r^2 corresponding to these *P*-values indicate that the majority of the variability in Δ SAP, Δ MAP and Δ DAP is not explained by the variation in SAP_{inv}, MAP_{inv} and DAP_{inv}. In addition, the results show that birthweight does not influence the variability in Δ SAP, Δ MAP and Δ DAP. Regarding the interaction between birthweight and invasive blood pressure values, only the interaction between DAP_{inv} and birthweight significantly contributes to the variability in Δ DAP ($P = 0.02$). Results suggest that low diastolic blood pressure tends to record overestimated oscillometric values: the higher the pressure the lower the overestimation. This overestimation tends to increase with increased birthweight. However, the value of r^2 in this interaction between DAP and birthweight has to be realized again: r^2 is only 0.6%, indicating that the majority of variability in Δ DAP depends on other variables.

Discussion

We investigated the agreement between invasively and oscillometrically determined systolic, diastolic and mean arterial pressures. The mean biases in SAP, DAP and MAP were significantly different from zero ($P < 0.001$), the limits of agreement were wide (Figs. 3a–d, Table 2). The noninvasive SAP may vary from 7.9 mmHg below to 10.9 mmHg above the invasive value. The noninvasive DAP may vary from 9.6 mmHg below to 7.6 mmHg above the invasive DAP value and noninvasive MAP may vary from 9.9 mmHg below to 5.3 mmHg above the invasive MAP value. In addition, we have shown that the relationship between SAP, DAP and MAP found with the noninvasive method was clearly different from that found with the invasive method. The noninvasive MAP% was 12.3% below the invasive MAP%, with limits of agreement of −23.0% to 1.8%.

The oscillometric method was first described in 1876 [26], and the first commercially available oscillometric monitor was produced in 1976 [27]. The principle of the oscillometric ABP device is described in detail and can be found elsewhere [27–30]. An inflatable cuff encircling a limb is used for compression of a limb and its vasculature. Pulsatile blood flow through an arterial limb vessel produces oscillations, which are transmitted to the cuff. Desufflation of the insufflated cuff creates an amplitude-diagram of oscillations. Identification of SAP, DAP and MAP occurs by reading the cuff pressure at predefined parameter identification points in the diagram of oscillations. These identification points for SAP, DAP and MAP can be selected in several different ways. For final ABP determination, the cuff pressure readings are converted into ABP values using an empirically determined calibration curve. Certain algorithms may be used to suppress measurement artefacts and to maintain a physiologically

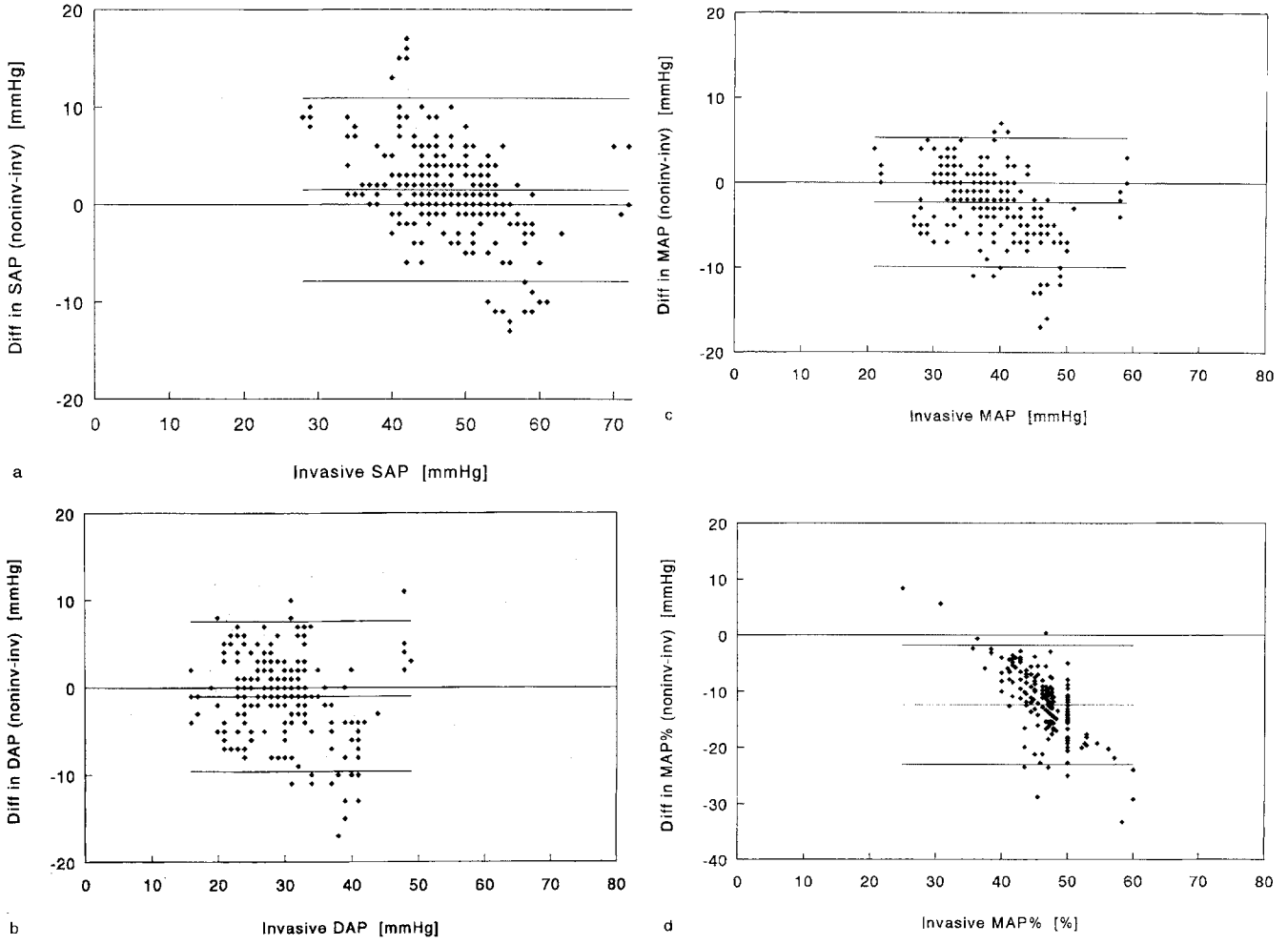

Fig. 3 **a** Differences in systolic arterial pressure (SAP) between oscillometric and invasive radial artery pressure measurements against invasive SAP. The *central line* represents the mean difference (bias) between the methods, the *two outlying lines* represent the mean difference in SAP ± 1.96 SD. **b** Differences in diastolic arterial pressure (DAP) between oscillometric and invasive radial artery pressure measurements against invasive DAP. The *central line* represents the mean difference (bias) between the methods, the *two outlying lines* represent the mean difference in DAP ± 1.96 SD. **c** Differences in mean arterial pressure (MAP) between oscillometric and invasive radial artery pressure measurements against invasive MAP. The *central line* represents the mean difference (bias) between the methods, the *two outlying lines* represent the mean difference in MAP ± 1.96 SD. **d** Differences in MAP% between oscillometric and invasive radial artery pressure measurements against invasive MAP%. The *central line* represents the mean difference (bias) between the methods, the *two outlying lines* represent the mean difference in MAP% ± 1.96 SD. *MAP%* the parameter describing the relationship between SAP, DAP and MAP using the equation MAP% = (MAP-DAP)/(SAP-DAP) × 100%

meaningful relationship between the parameters. This is usually proprietary information of the manufacturer.

Since this technique of oscillometric measurement has become available, a number of studies have been performed comparing oscillometric and invasive methods in adults [27, 31, 32], in children [15, 33] and in neonates [15–23]. In adults and children, a good correlation between the methods was found [27, 31, 33]. A good correlation between the two methods was also found in infants [15, 16, 18, 33]. Whereas correlation between the methods was reported to be reasonably good for determination of MAP in the cardiovascularly stable infant, the oscillometric technique may fail to detect low DAP [17, 19, 20]. However, studies on the precision of the oscillometric method for the individual infant are scarce. Briassoulis has shown that errors in the oscillometric measurements may be unacceptably large for the individual infant [23]. In addition, Wareham et al. reported limits of agreement ranging from 17 mmHg for MAP to 20 mmHg for SAP [22].

Since a high-fidelity measurement technique for blood pressure measurement is now available, it is possible to assess agreement between the methods. With this accurate method for invasive measurement we determined the limits of agreement and not the

correlation. The above-mentioned interval describes *the range* of intra-arterial values corresponding to each individual oscillometric value [25, 34]. The limits of agreement as found in the present study are thought to be unacceptably large for close pressure monitoring of the critically ill newborn infant admitted for intensive care.

The observed differences in ABP between the methods in our study may, in part, be explained as follows. Analysis of the relationships between SAP, DAP and MAP for both methods revealed that MAP is equal to a value of 34% of the pulse pressure (PP, defined as SAP − DAP) added to DAP in the oscillometric method, whereas MAP actually equals a value of 47% PP added to DAP in the invasive method (Table 1). This difference is significant ($P < 0.001$). This means that, according to the oscillometric device, the MAP can be approached by adding 34% PP to DAP, whereas MAP has to be approximated by adding 47% PP to DAP. As the relationship between SAP, DAP and MAP is part of the algorithms contributing to final ABP determination in the oscillometric device [personal communication with the manufacturer], deviations from invasive values will result. As the relationship between SAP, DAP and MAP as found in this oscillometric device is equal to the equation for adult peripheral artery waves [12, 27, 35 – 38], the incorporated algorithm may be derived from adult measurements or adult physiology. While this algorithm is adequate for the equipment for adult use, it fails in the module for neonatal use. These differences in algorithms in the relationship between SAP, DAP and MAP are due to differences in radial artery pressure wave contours between adults and newborns [14]. Usage of an algorithm adjusted to the newborn infant may improve agreement between the two methods.

Two issues regarding this study have to be considered. Firstly, although simultaneous measurements are ideally desired for this study, this is not possible due to the nature of the oscillometric device which performs measurement of blood pressure over many heart cycles (as explained above). The oscillometric device can only provide SAP, DAP and MAP at the end of the inflation/deflation cycle, while SAP and MAP have been determined several seconds before the values are displayed. As the invasive values displayed on the monitor are mean values based on eight cardiac cycles, respiratory fluctuations in blood pressure were eliminated. As quick blood pressure fluctuations are not expected to occur in newborn infants during the period of the inflation/deflation cycle (apart from above-mentioned eliminated respiratory fluctuations), we assigned the direct readings from the monitor at the end of the oscillometric cycle to be comparable with the direct reading. Secondly, potential bias due to comparison of measurements in two arms may be supposed. Earlier studies, however, have clearly demonstrated that differences between the left and right arm ABP values are negligible [29].

In conclusion, SAP, DAP and MAP as measured with the oscillometric device were significantly different from the intra-arterial values. Furthermore, limits of agreement between the oscillometric and invasive ABP measurement techniques were wide for SAP, DAP and MAP. This is due partly to the influence of the neonatal radial artery wave shape on ABP measurement. Presently, an algorithm for final ABP determination is used in newborn infants although it does not hold for them. Therefore, care should be taken when interpreting oscillometrically derived ABP values in critically ill neonates. We advise the manufacturer to reconsider calibration curves and the algorithm used for ABP determination.

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