Level of agreement between Nexfin non-invasive arterial pressure with invasive arterial pressure measurements in children

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Background. We compared Nexfin non-invasive arterial pressure measurements using a novel small finger cuff with intra-arterial pressure in the paediatric setting in order to establish the level of agreement between both methods.

Methods. The study included 41 children aged 2–16 yr admitted for surgery or paediatric intensive care with an intra-arterial catheter as part of standard monitoring. Values of systolic (SAP), diastolic (DAP), and mean arterial pressure (MAP) were obtained simultaneously from the intra-arterial catheter and the non-invasive Nexfin monitor. Data were analysed using intra-class correlation (ICC) coefficients and the Bland–Altman analysis.

Results. A non-invasive arterial pressure signal was obtained in the majority of patients. The reproducibility of arterial pressure measurements over time by both non-invasive and invasive techniques was high, with ICC coefficients ranging from 0.94 to 0.98. The Bland–Altman analysis for SAP, DAP, and MAP revealed a bias with 95% limits of agreement of $-13.5$ ($-39.7; +12.8$), $-0.2$ ($-12.8; +13.2$), and $-2.6$ ($-17.7; +12.5$) mm Hg, respectively. Linear regression suggested a weak correlation of SAP and the bias between intra-arterial and Nexfin SAP measurements (intercept 4.9 mm Hg, $b = 0.29; P = 0.01$).

Conclusions. Nexfin non-invasive arterial pressure measurements are feasible in paediatric patients. Nexfin accurately reflects the intra-arterial MAP and DAP curves, but seems to underestimate SAP compared with intra-arterial pressure. These results suggest that Nexfin may be used in low-to-moderate risk children without severe systemic hypotension, who require beat-to-beat haemodynamic monitoring but do not have an indication for invasive measurements.

Keywords: arterial pressure monitors; equipment and supplies, medical devices; paediatrics; peripheral arterial catheterization

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Editor’s key points

- The use of non-invasive arterial pressure monitors has been limited in children because accurate small finger cuffs have not been available.
- This study compared non-invasive measurements using the Nexfin device and new smaller finger cuffs with direct intra-arterial pressure.
- Mean and diastolic pressures were closely related, but the Nexfin underestimated systolic pressure.
- These new cuffs may be useful in some paediatric patients.
finger cuff.11 These studies showed that Finapres accurately tracked short-term arterial pressure changes, but with a significant measurement bias when compared with intra-arterial pressure measurements.11

Lemson and colleagues12 and Hofhuizen and colleagues11 evaluated the Nexfin device with a prototype small finger cuff that was specifically designed for children undergoing surgery and critically ill children. Both studies showed that non-invasive arterial pressure measurements obtained with this prototype finger cuff were reliable when compared with intra-arterial pressure measurements.11 12 However, in several patients, repeated finger cuff application attempts were necessary to obtain accurate arterial pressure signals.11

Recently, a next-generation small size and extra-small size finger cuff have been released. These are more comparable to the adult finger cuffs used for Nexfin non-invasive arterial pressure measurements. Therefore, in this study, we evaluated whether these new finger cuffs provide reliable non-invasive arterial pressure values by determining the level of agreement between the Nexfin measurements with intra-arterial pressure measurements in the paediatric setting.

**Methods**

**Subjects**

This prospective, observational clinical study evaluated 41 patients aged 2–16 yr who were undergoing surgery or were admitted to the paediatric intensive care unit (PICU) of the VU University Medical Centre (Amsterdam, The Netherlands). The Local Human Subjects Committee approved the study, and parental informed consent (2–12 yr) or patient informed consent (12–16 yr) was obtained in all cases. All subjects received an intra-arterial line as part of their standard anaesthetic or intensive care management.

**Non-invasive continuous arterial pressure measurements**

Non-invasive beat-to-beat arterial pressure measurements were performed using a Nexfin High Definition device (Nexfin HD monitor®, BMEYE, Amsterdam, The Netherlands) as described previously.4 5 13 The small-sized inflatable cuffs use photo plethysmography to measure beat-to-beat arterial pressure waveforms. From this finger arterial pressure, a brachial arterial pressure waveform is reconstructed, using a transfer function and level correction based on a vast clinical database. The Nexfin device automatically reconstructs the brachial arterial pressure waveform. The cuffs are available in the size XS, S, M, and L, corresponding to a finger circumference of 37–42, 42–51, 51–60, and 60–71 mm, respectively. The XS and S finger cuffs are shown in Figure 1. The finger cuff was selected based on the circumference of the mid-phalanx of the third finger. The Nexfin HD uses a built-in physiological calibration method (Physiocal®, BMEYE) to check and adjust the set point of the clamped artery after a maximum of 80 heartbeats.4 To correct for hydrostatic pressure differences between the finger and heart level, a heart reference system (HRS™) was applied to the finger and a reference part is placed at the level of the right atrium in the mid-axillary line.

**Invasive continuous arterial pressure measurement**

The intra-arterial catheter was inserted in the radial, brachial, or femoral artery, and the arterial pressure transducer was placed at the heart level. The transducer was first zeroed, and the line was subsequently flushed with NaCl 0.9% to remove air bubbles. The arterial catheter was connected to a pressure transducer (ART Safedraw: Becton Dickinson Critical Care System, Sandy, UT, USA) and linked via an invasive pressure module (Philips M1006B) to a monitoring system (Philips MP70) and an analogue input of the Nexfin device, which allowed simultaneous measurements of the non-invasive and intra-arterial pressure signals.

**Experimental procedure**

Non-invasive and invasive arterial pressure measurements were performed simultaneously in 36 sedated and five awake patients. The finger cuff was wrapped tightly around the finger and placed ipsilateral to the intra-arterial line. The hand was subsequently placed in a supine position. Method comparison started when Physiocal was 40 beats or more, or when 5 min had past and Physiocal remained below 40.14 The total measurement duration lasted at least 15 min to a maximum of 30 min. Significant changes in arterial pressure, heart rate, or both, triggered by talking, coughing, emotional stimuli, or postural changes of the hand or arm were noted on the Nexfin monitor.

**Data analysis**

Arterial pressure data were analysed using Frame-inspector (Frame inspector software version® 1.11.0.0, BMEYE) and BeatScope (BeatScope® 1.1.0.5 TNO TPD Biomedical, Amsterdam, The Netherlands). Statistical data analysis was carried out using a SPSS statistical software package version 17.0 (IBM, New York, NY, USA). Data are presented as mean (standard deviation, SD), median (inter-quartile range), or frequencies. For each subject, three distinct time points were selected at random from the total Nexfin measurement recording for arterial pressure measurement analysis. These time points were separated by at least 5 min of measurement time. The first measurement was conducted in the beginning of the measurement period, the second in the middle, and the third near the end of the measurement period. The time points were chosen irrespective of the specific phase in the respiratory cycle. A second researcher, who was blinded for the findings by the first reviewer, performed similar analyses in a subgroup of patients, and findings between both researchers were compared to evaluate the consistency of their findings. On each individual time point, three subsequent heartbeats with corresponding arterial pressure values were averaged, and the average was used for intra-class correlations (ICCs) over three time points. The selected arterial pressure values of the arterial line and...
Nexfin matched exactly with respect to the time point and time frame. ICCs with 95% confidence intervals were calculated using the SPSS two-way mixed reliability analysis option. Data were further analysed by the Bland–Altman analysis (GraphPad Prism 5.0, La Jolla, CA, USA). For this analysis, the nine heartbeats that were used for the ICC analyses were averaged. The Bland–Altman analysis provided the bias, so of the bias, and limits of agreement between both methods. The relation between systolic pressure measured using the arterial line or Nexfin \( n = 123 \) was evaluated by linear regression analysis using \((\text{ART} + \text{NEX})/2\) as the independent variable and \(\text{NEX} - \text{ART}\) as the dependent variable. The mean difference between direct arterial and Nexfin systolic (SAP) and diastolic arterial pressure (DAP) measurements between cuff sizes was analysed using the Kruskal–Wallis \( H \)-test for a three-group comparison (cuff sizes XS, S, and M). A \( P \)-value of \(< 0.05\) was considered as statistically significant.

### Results

#### Finger cuff application

The characteristics of the 41 children included in this study are presented in Table 1. In four cases, it was difficult at first to obtain an adequate non-invasive arterial pressure signal using the XS cuff, but this was solved by reapplication of the cuff to the finger and in all patients, acceptable non-invasive and invasive arterial pressure signals were obtained. In awake children, finger tickling was reported, but this was not perceived as painful or uncomfortable. Cyanosis of the fingertip was seen in a few patients. It was reversible in seconds after removing the finger cuff and without long-lasting side effects. Data were collected from all patients, resulting in an analysis of 369 heartbeats.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Patient characteristics. Data presented as median (inter-quartile range) or frequencies</th>
</tr>
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<tbody>
<tr>
<td>( n )</td>
<td>41</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>9 (2–17)</td>
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<tr>
<td>Male/female (( n ))</td>
<td>29/12</td>
</tr>
<tr>
<td>Length (m)</td>
<td>1.35 (1.15–1.67)</td>
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<tr>
<td>Weight (kg)</td>
<td>34 (18–56)</td>
</tr>
<tr>
<td>Body mass index (kg m(^{-2}))</td>
<td>18 (15–20)</td>
</tr>
<tr>
<td>Intubation (yes/no)</td>
<td>35/6</td>
</tr>
<tr>
<td>Intensive care/operating theatre</td>
<td>26/15</td>
</tr>
<tr>
<td>Site of arterial catheter (radial/brachial/femoral)</td>
<td>36/2/3</td>
</tr>
<tr>
<td>Left/right</td>
<td>21/20</td>
</tr>
<tr>
<td>Cuff size (XS/S/M/L)</td>
<td>13/14/12/2</td>
</tr>
</tbody>
</table>
Table 2 ICC coefficients for non-invasive (Nexfin) and invasive (intra-arterial line) arterial pressure measurements. ICC coefficients for non-invasive and invasive arterial pressure measurements. I, II, and III represent three consecutive time points. SAP, systolic arterial pressure; DAP, diastolic arterial pressure; MAP, mean arterial pressure. Arterial pressure values presented as mean (SD). ICC is presented as mean (range)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nexfin</td>
<td>SAP (mm Hg)</td>
<td>96 (23)</td>
<td>96 (21)</td>
<td>96 (22)</td>
</tr>
<tr>
<td></td>
<td>DAP (mm Hg)</td>
<td>60 (14)</td>
<td>60 (13)</td>
<td>60 (13)</td>
</tr>
<tr>
<td></td>
<td>MAP (mm Hg)</td>
<td>74 (17)</td>
<td>74 (15)</td>
<td>74 (16)</td>
</tr>
<tr>
<td>Arterial line</td>
<td>SAP (mm Hg)</td>
<td>111 (26)</td>
<td>109 (25)</td>
<td>109 (25)</td>
</tr>
<tr>
<td></td>
<td>DAP (mm Hg)</td>
<td>60 (12)</td>
<td>60 (12)</td>
<td>60 (13)</td>
</tr>
<tr>
<td></td>
<td>MAP (mm Hg)</td>
<td>77 (17)</td>
<td>76 (16)</td>
<td>76 (17)</td>
</tr>
</tbody>
</table>

Association of non-invasive and invasive arterial pressure measurements
The ICC coefficients for non-invasive and invasive arterial pressure measurements for three consecutive time points are presented in Table 2. The ICC for SAP, DAP, and mean arterial pressure (MAP) was high for non-invasive and invasive arterial pressure measurements (range 0.94–0.98).

Level of agreement between non-invasive and invasive measurements
Figure 2 represents the Bland–Altman analyses for SAP, MAP, and DAP with bias and limits of agreement between non-invasive and invasive arterial pressure measurements. The mean (SD) bias for SAP, MAP, and DAP estimated were -13.5 (13.4), -2.6 (7.7), and 0.2 (6.6) mm Hg, respectively. The corresponding levels of agreement ranged from -39.7 to 12.8 mm Hg for the SAP, from -17.7 to 12.5 mm Hg for the MAP, and from -12.8 to 13.2 mm Hg for the DAP. Linear regression revealed a weak correlation between SAP and the bias between intra-arterial and Nexfin SAP measurements (intercept 4.9 mm Hg, β standardized coefficient = −0.29; P=0.01).

Relation of cuff size with arterial and Nexfin arterial pressure differences
Figure 3 shows the difference between intra-arterial and Nexfin SAP (Fig. 3a) or DAP (Fig. 3b) for the XS, S, and M cuff sizes. Values obtained with a large cuff size were removed from the analysis due to sample size limitations. The difference between intra-arterial and Nexfin measurements was larger for systolic than diastolic pressure measurements. We found no difference between cuff sizes with respect to the mean difference between intra-arterial and Nexfin measurements for the distinct time points 1, 2, and 3 that correspond with the time points in Table 2. However, the inter-quartile range for the difference in intra-arterial and Nexfin diastolic pressure was the highest for the XS cuff and the lowest for the M cuff.

Discussion
In this study, we found that Nexfin non-invasive finger arterial pressure measurements were feasible to perform in the paediatric setting. In particular, the novel Nexfin finger cuff was well tolerated in children without reported discomfort. The reproducibility of SAP, DAP, and MAP measurements over time was high for both Nexfin and intra-arterial measurements. Our study further demonstrates a good level of agreement for DAP and MAP measurements between Nexfin and intra-arterial pressure measurements in children.
We however observed an underestimation of Nexfin systolic pressure when compared with invasive measurements. Our study supports the use of Nexfin arterial pressure measurements in children.

The Association of Medical Instrumentation (AAMI) for validation of new arterial pressure devices advises that the mean difference between a new device and the gold standard should be lower than 5 mm Hg, with an SD of 8 mm Hg. In our study, we found that Nexfin DAP and MAP measurements are within these guidelines, whereas the deviation between Nexfin and intra-arterial systolic pressure values diverted from the acceptable AAMI validation limits. The underestimation of Nexfin systolic pressure measurements was also reported by Lemson and colleagues. In contrast to their study, we however showed a good level of agreement for diastolic and mean pressure for Nexfin and intra-arterial measurements.

We further evaluated the relation between the difference in intra-arterial and Nexfin systolic pressure using linear regression analysis. Our findings suggested that the difference between intra-arterial and Nexfin systolic pressure measurements slightly decreases with increasing arterial pressure. There is currently no validated explanation for this pressure-dependent effect on the agreement between intra-arterial and Nexfin systolic pressure measurements.

Dorlas and colleagues and Wesseling and colleagues reported previously that the brachial and non-invasive finger arterial pressure shows a systolic pressure difference of about 10 mm Hg, and that this difference is particularly augmented in the case of vasoconstriction due to amplification of the pressure waveform. In contrast to our findings, this augmentation induces an increased finger to brachial amplitude ratio, suggesting an overestimation of the arterial systolic pressure by the non-invasive finger cuff measurements. Moreover, the small distance between the Nexfin finger cuff position and the intra-arterial line, and consequent differences in arterial pressure waveform transit time, may not be explanative for the differences in SAP.

![Fig 3 Mean difference between arterial and Nexfin measurements for SAP (a) and DAP (b) for the different cuff sizes XS, S, and M. XS-1, XS-2, and XS-3 refer to the three different measurement time points.](https://academic.oup.com/bja/article/109/4/609/237680)
measurements. Using a Finapres device, Tanaka and Thulnesius\textsuperscript{18} showed that overestimation of the systolic pressure by finger cuff measurements seems to be dependent on local vasoconstriction, and can be modulated by finger heating. Although others earlier reported an underestimation of the finger systolic pressure in children\textsuperscript{12} or elderly\textsuperscript{19} when compared with an intra-arterial or intra-brachial line, these studies did not find an explanation for this discrepancy. Future studies should reveal whether our findings can be attributed to the low age of our study population or reflect a measurement artifact originating from the Nexfin arterial pressure measurement device or finger cuffs.

This study does not provide information regarding the ability of Nexfin to accurately track changes in arterial pressure, and this should be investigated in future studies. The differences between non-invasive and intra-arterial systolic pressure measurements may also be explained by the variation in applied finger cuffs in the present study, with cuff sizes ranging from XS to L. In particular, older children may require larger cuff sizes. One might assume that the MAP, SAP, and DAP all reflect a similar finger cuff size-dependent difference in the relation between non-invasive and intra-arterial pressure. Despite the observed discrepancy between non-invasive and invasive systolic pressure values, we found a high level of agreement for mean and diastolic pressure values irrespective of the cuff size. Moreover, an evaluation of the difference in non-invasive and intra-arterial SAP and DAP for three different cuff sizes revealed no cuff size-dependent effect on the difference between the Nexfin and the intra-arterial line measurements. However, the variation in the difference between the intra-arterial and Nexfin diastolic pressure measurements was the highest for the XS cuff and the lowest for the M cuff, suggesting that the application of the XS cuff may be associated with the highest variation in arterial pressure measurements.

The present study describes the application of a new model of XS and S finger cuffs in children. Others described that the use of these finger cuffs in awake children may be unpleasant due to the inflation pressure.\textsuperscript{11} 12 In our study, five out of 41 children were awake during the Nexfin arterial pressure measurements, and none complained about the use of the finger cuff as neither being unpleasant nor being painful. A proper cuff fit in the case of the application of the smallest finger cuff (XS) was in some cases, however, difficult. In some children, the cuff had to be reapplied several times before obtaining an accurate signal, which may be a limitation of the Nexfin device in the case of emergency situations. These difficulties did not occur in the case of larger children where a larger cuff size was used.\textsuperscript{14}

The intra-arterial catheter measurements were performed at different positions in the arterial tree, that is, the femoral, brachial, and (mostly) radial. Owing to pulse wave amplification reflections and resistance to blood flow, pressure waves may differ in shape and mean value at the invasive measurement sites compared with the Nexfin measurement at the finger. However, according to Andriessen and colleagues,\textsuperscript{9} \textsuperscript{10} the peripheral arterial pressure waveforms and values in children appear to deviate less from centrally measured arterial pressures compared with adults because of the closer proximity of these sites.

We demonstrated that Nexfin accurately reflects the intra-arterial MAP and DAP curves, but with an underestimation for SAP. Nexfin beat-to-beat arterial pressure measurements are feasible to perform in the paediatric population with a low failure rate. Our study further suggests that the applicability of Nexfin arterial pressure measurements in the paediatric setting should be limited to specific patient populations. First, an underestimation of the SAP by the Nexfin device may become clinically relevant in patients with a low systemic arterial pressure due to shock or haemorrhage. In these patients, Nexfin arterial pressure measurements should probably not be applied, as the underestimation of the SAP may hint towards aggravation of the medical condition of the patient. Future evaluation of the threshold values for clinical decision-making can be interchangeable between Nexfin and intra-arterial pressure measurements. This further suggests that improvement of the XS finger cuff in order to reduce measurement variation may enhance the level of agreement between Nexfin and intra-arterial pressure measurements in children.

In conclusion, these findings support the use of Nexfin in the paediatric setting, especially in low-to-moderate risk children who require beat-to-beat haemodynamic monitoring without an indication for invasive intra-arterial pressure measurements. Although intra-arterial pressure measurements remain the gold standard, their applicability is limited and may be hampered by technical failure. In these cases, Nexfin arterial pressure measurements could be used as an alternative. Unfortunately, the application of Nexfin measurements is not possible in children up to 2 yr of age. Further studies are needed to further evaluate systolic pressure measurements using the Nexfin, particularly in children with hypotension caused by vascular dilatation or pathophysiological circumstances such as shock or haemorrhage.

Declaration of interest
C.B. was a lecturer during a Nexfin symposium at the ESA congress in Amsterdam, 2011, but received no financial compensation for this lecture.

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Non-invasive continuous arterial pressure in children


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