Non-invasive continuous blood pressure monitoring of tachycardic episodes during interventional electrophysiology

Roberto Maggi, Valentina Viscardi, Toshiyuki Furukawa, and Michele Brignole*

Department of Cardiology, Arrhythmologic Centre, Ospedali del Tigullio, Lavagna, Italy

Received 25 February 2010; accepted after revision 12 August 2010; online publish-ahead-of-print 13 September 2010

Aims
We thought to evaluate feasibility of continuous non-invasive blood pressure monitoring during procedures of interventional electrophysiology.

Methods and results
We evaluated continuous non-invasive finger blood pressure (BP) monitoring by means of the Nexfin device in 22 patients (mean age 70 ± 24 years), undergoing procedures of interventional electrophysiology, in critical situations of hypotension caused by tachyarrhythmias or by intermittent incremental ventricular temporary pacing till to the maximum tolerated systolic BP fall (mean 61 ± 14 mmHg per patient at a rate of 195 ± 37 bpm). In all patients, Nexfin was able to detect immediately, at the onset of tachyarrhythmia, the changes in BP and recorded reliable waveforms. The quality of the signal was arbitrarily classified as excellent in 11 cases, good in 10 cases, and sufficient in 1 case. In basal conditions, calibrations of the signal occurred every 49.2 ± 24.3 s and accounted for 4% of total monitoring time; during tachyarrhythmias their frequency increased to one every 12.7 s and accounted for 19% of total recording duration. A linear correlation for a range of BP values from 41 to 190 mmHg was found between non-invasive and intra-arterial BP among a total of 1055 beats from three patients who underwent simultaneous recordings with both methods (coefficient of correlation of 0.81, \( P < 0.0001 \)).

Conclusion
In conclusion, continuous non-invasive BP monitoring is feasible in the clinical practise of an interventional electrophysiology laboratory without the need of utilization of an intra-arterial BP line.

Keywords
Electrophysiological study • Blood pressure monitoring • Tachycardia • Ventricular pacing

Introduction
It is common practise, during some invasive electrophysiology procedures, to continuously monitor arterial blood pressure (BP) by means of an intra-arterial line. This procedure implies the risk of complications due to the vascular access, an increase of the procedural time, and causes some discomfort to the patient.

Continuous (beat-to-beat) non-invasive BP measurement is widely used in research, anaesthesiology, and tilt laboratories. The most used devices are those which use the method of Penaz to record the arterial waveform indirectly from a finger. Studies on its accuracy have suggested little systematic bias vs. intra-arterial pressure or non-invasive intermittent BP measurements.\(^1,2\)

We thought to evaluate feasibility continuous non-invasive BP monitoring during procedures of interventional electrophysiology.

Method
Continuous (beat-to-beat) non-invasive BP was measured with the Nexfin monitor (BMEYE B.V, Amsterdam, The Netherlands) which uses the latest implementation of the Finapres method.\(^3\) The Finapres method is based on the volume-clamp methodology of
Arterial blood volume in the finger is determined with an optical plethysmograph mounted in an inflatable cuff system. A controlled pneumatic cuff system around the finger clamps the artery at its ‘unloaded’ volume, so that transmural pressure is zero throughout the cardiac cycle. The unloaded volume is detected by periodical calibration called ‘Physiocal’ (Physiological Calibration). During a Physiocal, cuff air pressure is held at varying steady levels and the plethysmogram is observed by the pulsating intra-arterial pressure. The amplitude and shape of plethysmogram determine the volume-clamp level and servo system loop gain automatically. This is regularly repeated during the measurement as the unloaded volume may change with different physiological states of the vasculature. The duration of a standard Physiocal is one or two beats, but can be prolonged in case of low signal/low perfusion. The finger cuff pressure waveform equals finger arterial pressure and can be measured for several hours. The Nexfin, using the same basic principles, has been redesigned to allow the use of present-day hardware, software, and physiological models. The finger cuffs have been redesigned with modern optical components for better signal to noise ratio.

Non-invasive continuous blood pressure monitoring

We evaluated a non-invasive continuous BP monitoring system in 22 patients undergoing procedures of interventional electrophysiology in critical situations of hypotension caused by tachyarrhythmias or by temporary ventricular pacing rates ranging between 100 and 280 bpm. An appropriate-sized finger cuff was applied to the midphalanx of the left middle finger. The cuffed finger was positioned at the midthoracic level to avoid hydrostatic pressure differences. Attention was paid to avoid cold fingers during initiation of the measurement that are usually associated with reflex arteriolar vasoconstriction and can interfere with proper measurement of the plethysmogram. Artificial pacing was performed, by repeated intermittent sequences of pacing for 30 s, at increasing steps of 20 bpm, till the maximum tolerated BP fall, or the loss of 1:1 ventricular capture.

The following outcomes were measured: (i) quality of the pulse waveforms (at rest and during high rates), evaluated by an independent observer who was asked to classify it arbitrarily as excellent (waveforms of good shape, amplitude, velocity and area, dicrotic notch visible, very similar to intra-arterial signal), good (as the previous but sometimes with non-physiological abrupt rising pressure waves and artefacts), sufficient (waveforms of different shape, amplitude, velocity and area, frequent non-physiological abrupt rising pressure waves but still adequate to trust, dicrotic notch not visible and frequent calibrations), and insufficient (impossibility of recording adequate waveforms; Figures 1 and 2); (ii) frequency of calibrations (and their percentage on total monitoring time), at baseline and during incremental rates; (iii) time delay between onset of tachyarrhythmia and BP wave detection. In addition, in three patients, the intra-patient linear correlation between non-invasive and invasive BP value changes during incremental high rates were evaluated by means of simultaneous measurements of non-invasive and intra-arterial BP (femoral in two and radial in one) during the supine baseline state and during ventricular temporary pacing. Intra-arterial femoral BP was measured by means of the EMS device (Mennen Medical, Israel). The BP values for each individual beat were manually analysed. The resulting linear regression equation was calculated and the comparison between the two methods was made by means of the Pearson coefficient of correlation.

Results

The characteristics for the 22 patients (18 males) are shown in the Table 1. Structural heart disease was present in 11 of them (ischaemic in 5, valvular in 4, dilated in 2); the others had primary arrhythmias.

During baseline recordings, the quality of the signal was arbitrarily classified as excellent in 14 cases (Figures 1 and 2A), good in 7 cases (Figure 2B), and sufficient in 1 case (Figure 2C). The coefficient of correlation between Nexfin BP and automatic intermittent brachial cuff BP was 0.85 (regression equation: y = 0.86 × 21.9 (P = 0.0001).

In total, 102 episodes of tachyarrhythmia were recorded in 22 patients (incremental ventricular pacing in 100 cases and induced ventricular tachycardia in 2 cases): of these, 79 episodes caused a fall in systolic BP to an absolute value <100 mmHg with a mean fall of 64.9 ± 22.3 mmHg. At the onset of tachyarrhythmia, Nexfin was able to immediately detect the changes in BP in all patients.
Figure 2  (A) Baseline Nexfin blood pressure waves in a patient in whom it was classified as excellent (waveform of good shape, amplitude, velocity and area, dicrotic notch visible, very similar to invasive signal). (B) Baseline Nexfin blood pressure waves in a patient in whom it was classified as good (waveforms as the previous but sometimes non-physiological abrupt rising pressure and artefacts). (C) Baseline Nexfin blood pressure waves in a patient in whom it was classified as sufficient (waveforms of different shape, amplitude, velocity and area, non-physiological abrupt rising pressure waves, but still adequate to trust, dicrotic notch not visible and frequent calibrations); the different systolic blood pressure peaks are consistent with different blood pressure values due to rhythm irregularity so that waveforms seem still adequate to trust.
and recorded reliable waveforms for the whole duration of the tachyarrhythmia. Specifically, Nexfin was able to detect BP waveforms even in the recordings in which BP suddenly dropped to \(<100\) mmHg (Figures 3–5). Whereas in basal conditions the system performed calibration of the signal every 49.2 \(\pm\) 24.3 s (or 52.8 \(\pm\) 20.4 beats) for 2.5 s each corresponding to 4% of total monitoring time, during tachyarrhythmias the frequency of calibrations increased to one every 12.7 s (40.1 \(\pm\) 23.7 beats) on average: in total there were 260 calibrations during 3.323 s of recording, corresponding to 19% of total recording duration. In particular, there were 23 episodes of ventricular tachyarrhythmia at a heart rate \(\geq 200\) bpm (mean heart rate 221 \(\pm\) 24 bpm). During these episodes the mean BP measured with Nexfin was 101.3 \(\pm\) 23.7 mmHg; calibrations occurred every 12.5 s (41.3 \(\pm\) 20.6 beats) corresponding to 21.4% of total recording time. The quality of the signal was arbitrarily classified as excellent in 11 cases, good in 10 cases, and sufficient in 1 case.

### Table 1 Characteristics for the 22 study patients

|                           | Range     | Median (P25; P75) | Mean \(\pm\) SD |
|---------------------------|-----------|-------------------|-----------------|
| Age, years                | 20–98     | 77 (62; 82)       | 70 \(\pm\) 24   |
| Height, cm                | 152–180   | 173 (169; 178)    | 172 \(\pm\) 7   |
| Weight, Kg                | 50–85     | 73 (65; 79)       | 72 \(\pm\) 9    |
| Baseline intermittent systolic BP by automatic brachial cuff device\(^a\), mmHg | 80–180 | 146 (121; 154) | 140 \(\pm\) 26 |
| Baseline continuous systolic BP by finger Nexfin\(^b\), mmHg | 88–184 | 143 (120; 157) | 138 \(\pm\) 26 |
| Tachycardia sequences, bpm | 100–280   | 160 (120; 180)    | 159 \(\pm\) 42   |
| Maximum heart rate per patient | 140–280   | 180 (160; 220)    | 195 \(\pm\) 37   |
| Minimum measured BP per patient | 41–87     | 60 (49; 73)       | 61 \(\pm\) 14   |

P25 and P75 give the 25th and 75th percentiles.
BP, blood pressure.
\(^a\)Value determined by average of three measurements per patient.
\(^b\)Value determined by average of measurements performed during 30 s per patient.

**Figure 3** Simultaneous beat-to-beat comparison between invasive and Nexfin blood pressure waves during a period of 30 s of ventricular pacing at 140 bpm.
**Figure 4** Patient’s case. Blood pressure curve during ventricular pacing at 240 bpm for 30 s. Automatic calibration of the system for a period of 2.5 s toward the end of the pacing period.

**Figure 5** Ventricular pacing at increasing rate from 100 to 220 bpm in an 81-year-old patient. Blood pressure curves are sometimes interrupted by periods of 2.5 s of automatic calibration of the system. Pacing at 220 bpm was prematurely interrupted because the patient had impending syncope. At heart rates of 180 and 200 bpm there are two classical examples of artefacts.
Non-invasive continuous blood pressure monitoring

A total of 1055 beats (from 16 sequences of pacing at rate ranging 100–240 bpm) was manually analysed in the three patients who underwent simultaneous recording of Nexfin and intra-arterial BP. A linear correlation was found between the two methods for a range of BP values from 41 to 190 mmHg. Each point is the blood pressure value of any single beat. The values of each patient are of the same colour. The blood pressure measurements, baseline and during ventricular pacing at increasing rates from 100 to 240 bpm, are reported. The black line is the linear regression line. The less than perfect linear correlation in two patients may be due to the use of the femoral artery pulse tracing which is known to provide quite different values and waveforms from more central vessels.

**Figure 6** Correlation between beat-to-beat systolic Nexfin blood pressure and invasive blood pressure recorded simultaneously in three patients for a wide range of blood pressure values from 41 to 190 mmHg. Each point is the blood pressure value of any single beat. The values of each patient are of the same colour. The blood pressure measurements, baseline and during ventricular pacing at increasing rates from 100 to 240 bpm, are reported. The black line is the linear regression line. The less than perfect linear correlation in two patients may be due to the use of the femoral artery pulse tracing which is known to provide quite different values and waveforms from more central vessels.

Finally, we have successfully replaced intra-arterial BP monitoring with Nexfin BP monitoring during 100 standard procedures of invasive electrophysiology. We were able to obtain reliable BP monitoring in all except two patients who had insufficient quality of the signal due to severe impairment of finger arterial vascularization as a consequence of systemic atherosclerosis.

**Discussion**

We showed that continuous non-invasive finger BP monitoring provides reliable arterial waveforms even in critical situations of sudden onset of high and very high ventricular rate and of severe hypotension such as those observed in a laboratory of electrophysiology. The beat-to-beat waves are immediately detected at the onset of tachyarrhythmia (thus providing an immediate parameter of the haemodynamic status of the patient even before the onset of hypotensive symptoms) and, even if detection is interrupted by frequent episodes of calibration, the percentage of measured beats is largely sufficient for a continuous monitoring of the haemodynamic status of the patient. Therefore, non-invasive finger BP monitoring can safely replace the intra-arterial monitoring during interventional electrophysiology procedures.

The Finapres method, of which Nexfin is an evolution, has been utilized in a variety of settings, such as drug-induced hypotension during hypotensive anaesthetic techniques, tilt testing, Valsalva manoeuvre, and exercise stress tests. However, it has not yet been used during interventional electrophysiology.

The validation of non-invasive continuous BP monitoring systems is outside the scope of this study. However, studies on the accuracy of Finapres have suggested little systematic bias vs. intra-arterial pressure but substantial variability. In combined data from 20 published studies for a total of 449 patients, the average systolic bias was $2.2 \pm 12.4$ mmHg. The average precision was $12.1 \pm 8.4$ mmHg. The calculated percentage of Finapres systolic values expected to fall within $\pm 10$ mmHg of the direct intra-arterial pressure was 73.1%. Although the observed variability creates some concern in research trials, there is general agreement that Finapres accuracy and precision usually suffice for reliable tracking in the clinical practice. Using the Nexfin on the same basic principles of Finapres, we assumed that its accuracy is the same as that of Finapres. In addition, in a recent study performed in 104 subjects (aged 18–95 years), Nexfin provided accurate measurement of BP with good within-subject precision when compared with brachial auscultatory BP measurements (Riva-Rocci/Korotkoff). Brachial systolic BP was 129 (interquartile range 115, 150). Nexfin difference was 5.4 (–1.7, 11.0) mmHg; within-subject precisions was $–2.2 \pm 2.3$. These results are fairly consistent with the correlation observed in this study between Nexfin and intermittent non-invasive BP baseline measures.

The impossibility of measuring the plethysmogram in the finger due to the combination of vascular disease, ambient cold temperature and other reasons is reported to occur in the literature in $\sim 1\%$ of patients. We observed a similar $2\%$ failure rate in our patients.

**Limitations**

The study population was small and polymorphic. The potential difference between Nexfin and Finapres or similar devices is that Nexfin’s finger cuffs have been redesigned with modern optical components for better signal to noise ratio and that Nexfin provides reconstructed brachial arterial BP while Finapres gave raw finger arterial BP values. In this study, Nexfin was not compared with other available devices; thus, the results of this study apply to the Nexfin device and may not necessarily be reproduced with other devices measuring continuous non-invasive BP. Although the correlation with invasive BP was sufficiently validated with Finapress, this correlation in critical situations of hypotension caused by tachyarrhythmias was done in this study only in three patients. As mentioned before, the validation of non-invasive continuous BP monitoring system was outside the scope of this study. In this study, we rather looked for intra-patient linear correlation between non-invasive and invasive BP value changes during incremental high rates and within a wide range of BP values (from 41 to 190 mmHg). Indeed, in the clinical practise of interventional electrophysiology, an immediate recognition of sudden
changes of BP at the onset of tachyarrhythmia is an important safety parameter which is partially independent of the accuracy of the absolute BP values and guides the physician’s decision whether to interrupt the arrhythmia immediately. We found that Nexfin was able to detect immediately sudden changes of BP at the onset of tachyarrhythmia and that these changes were linearly correlated with invasive measures, thus providing to be a reliable method for the safety of the patient and useful for guiding physician’s decisions.

Conclusions
Continuous non-invasive finger BP monitoring is feasible and reliable in the clinical practise of an interventional electrophysiology laboratory without the need of utilization of an intra-arterial BP line.

Conflict of interest: none declared.

Funding
A Nexfin device was sponsored for this study by BMEYE B.V., Amsterdam, The Netherlands, but, apart from the device, the authors did not receive any other compensation for performing the study. Funding to pay the Open Access publication charges was provided by BMEYE B.V., Amsterdam.

References
1. Silke B, McAuley D. Accuracy and precision of blood pressure determination with the Finapres: an overview using re-sampling statistics. J Hum Hypertens 1998;12:403–9.
2. Imholz BP, Wieling W, van Montfrans GA, Wesseling KH. Fifteen years experience with finger arterial pressure monitoring: assessment of the technology. Cardiovasc Res 1998;38:605–16.
3. Eeftinck Schattenkerk DW, van Lieshout JJ, van den Meiracker AH, Wesseling KR, Blanc S, Wieling W et al. Nexfin noninvasive continuous blood pressure validated against Riva-Rocci/Korotkoff. Am J Hypertens 2009;22:378–83.
4. Westerhof BE, Gunen I, Parati G, Groppelli A, Van MG, Wieling W et al. Variable daynight bias in 24-h non-invasive finger pressure against intrabrachial artery pressure is removed by waveform filtering and level correction. J Hypertens 2002;20:1981–6.
5. Goudilich F, Prenza A, Wesseling KH. Models of brachial to finger pulse wave distortion and pressure decrement. Cardiovasc Res 1997;33:698–705.
6. Bogert LWJ, Harms MP, Pott F, Secher NH, Wesseling KH, Van Lieshout JJ. Reconstruction of brachial pressure from finger arterial pressure during orthostasis. J Hypertens 2004;22:1873–80.
7. Penaz J. Photoelectric measurement of blood pressure, volume and flow in the finger. Digest of the 10th International Conference on Medical and Biomedical Engineering, Dresden, Germany, 1973, p. 104.
8. Wesseling KH, De Wijn B, Van der Hoeven GMA, Van Goudoever J, Settels JJ. Physiocal, calibrating finger vascular physiology for Finapres. Homeostasis 1995;36:67–82.
9. Imholz BPM, Langewouters GJ, Van Montfrans GA, Parati G, Van Goudoever J, Wesseling KH et al. Feasibility of ambulatory, continuous 24-hour finger arterial pressure recording. Hypertension 1993;21:65–73.
10. Epstein RH, Kaplan S, Leighton BL, Nairn MC, DeSimone CA. Evaluation of a continuous noninvasive blood pressure monitor in obstetric patients undergoing spinal anesthesia. J Clin Monit 1989;5:157–63.
11. Epstein RH, Bartkowski RR, Hulfnagle S. Continuous noninvasive finger blood pressure during controlled hypotension. A comparison with intraarterial pressure. Anesthesiology 1991;75:796–803.
12. Atken HA, Todd JG, Kenny GN. Comparison of the Finapres and direct arterial pressure monitoring during profound hypotensive anaesthesia. Br J Anaesth 1991;67:36–40.
13. Imholz BPM, Settels JJ, van den Meiracker AH, Wesseling KH, Wieling W. Noninvasive continuous blood pressure measurement during orthostatic stress compared to intra-arterial pressure. Cardiovasc Res 1990;24:214–21.
14. Jelisma WT, Imholz BPM, van Goudoever J, Wesseling KH, van Lieshout JJ. Finger arterial versus intra-brachial pressure and continuous cardiac output during head-up tilt testing in healthy subjects. Clin Sci 1996;91:193–200.
15. Petersen MEV, Williams TR, Sutton R. A comparison of non-invasive continuous finger blood pressure measurement (Finapres) with intra-arterial pressure during prolonged head-up tilt. Eur Heart J 1995;16:1647–54.
16. Friedman DB, Jensen FB, Matzen S, Secher NH. Non-invasive blood pressure monitoring during head-up tilt using the Penaz principle. Acta Anaesthesiol Scand 1990;34:519–22.
17. Parati G, Casadei R, Groppelli A, Di Rienzo M, Mancia G. Comparison of finger and intra-arterial blood pressure monitoring at rest and during laboratory testing. Hypertension 1989;13:647–55.
18. Rongen GA, Bos WJW, Lenders JMP, van Montfrans GA, van Lier HJJ, van Goudoever J et al. Comparison of intra-brachial and finger blood pressure in healthy elderly volunteers. Am J Hypertens 1995;8:237–48.
19. Slik S, Spiers JP, Boyd S, Graham G, McParland G, Scott ME. Evaluation of non-invasive blood pressure measurement by the Finapres method at rest and during dynamic exercise in subjects with cardiovascular insufficiency. Clin Auton Res 1994;4:49–56.
20. Slik S, Spiers JP, Boyd S, Graham G, McParland G, Scott ME. Evaluation of non-invasive blood pressure measurement by the Finapres method at rest and during dynamic exercise in subjects with cardiovascular insufficiency. Clin Auton Res 1994;4:49–56.
21. Kurki TS, Pirainen HL, Kurki PT. Non-invasive monitoring of finger arterial pressure inpatients with Raynaud phenomenon: effects of exposure to cold. Br J Anaesth 1995;75:558–63.