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REVIEW

Validity and success rate of noninvasive mean arterial blood pressure measurements in cf-LVAD patients: A technical review

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Abstract

Background: The life expectancy of patients with a continuous flow left ventricular assist device (cf-LVAD) is increasing. Adequate determination and regulation of mean arterial pressure (MAP) is important to prevent adverse events. Given the low pulsatility characteristics in these patients, standard blood pressure equipment is inadequate to monitor MAP and not recommended. We provide an overview of currently available noninvasive techniques, using an extensive search strategy in three online databases (Pubmed, Scopus and Google Scholar) to find validation studies using invasive intra-arterial blood pressure measurement as a reference. Mean differences with the reference values smaller than 5 ± 8 mm Hg were considered acceptable.

Observations: After deduplication, screening, and exclusion of incorrect sources, eleven studies remained with 3139 successful MAP measurements in 386 patients. Four noninvasive techniques, using Doppler, pulse oximetry, finger cuff volume clamp, or slow upper arm cuff deflation, were identified and evaluated for validity and success rate in cf-LVAD patients. Here, a comprehensive technical background of the blood pressure measurement methods is provided in combination with a clinical use comparison. Of the reported noninvasive techniques, slow cuff devices performed most optimally (mean difference 1.3 ± 5.2 mm Hg).

Conclusions: Our results are encouraging and indicate that noninvasive blood pressure monitoring options with acceptable validity and success rate are available. Further technical development and validation is warranted for the growing population of patients on long-term cf-LVAD support.

KEYWORDS

blood pressure, LVAD, noninvasive measurement, technical review

Steven Lankheet, Martijn M. Pieterse, Robin Rijnhout, and Emma Tuerlings contributed equally and share first authorship, Berend E. Westerhof, and Marish I. F. J. Oerlemans contributed equally and share last authorship.

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1 | INTRODUCTION

Heart failure is a major public health issue with an estimated prevalence of over 63.4 million patients worldwide. This prevalence is expected to rise in the coming years due to the aging of the population and increasing risk factors like hypertension and diabetes mellitus.[1] For patients with end-stage heart failure, heart transplantation is currently the therapy of choice in carefully selected patients.[2] Given the shortage of donor hearts, long-term mechanical circulatory support by continuous-flow left ventricular assist devices (cf-LVADs) has become a promising alternative for this patient group.[3] Life expectancy with cf-LVAD has improved considerably, approaching post-transplant survival after 2 years of about 83%.[2,4] At the same time, long-term survival is accompanied by an increasing incidence of adverse events.[5,6]

One of the most important factors related to adverse events is an increased mean arterial pressure (MAP).[7] An increased MAP, which is directly linked to an increased afterload, can cause various adverse events such as pump thrombosis, cerebrovascular accidents, and aortic insufficiency.[8] To minimize the prevalence of adverse events, the International Society for Heart and Lung Transplantation guidelines of 2020 recommend a MAP lower than 80–85 mm Hg.[9] Therefore, adequate blood pressure (BP) monitoring and regulation is necessary for favorable long-term patient prognosis.

Conventional BP monitors rely on the pulsating property of the BP. Because of the low pulsatility characteristics of BP in patients with a cf-LVAD, such devices have a low success rate for the measurement of BP. An indwelling arterial catheter (A-line) is the gold standard for blood pressure measurement; however, this technique is too invasive and cumbersome for follow-up measurements and impossible in the outpatient setting.[10,11]

For our study we performed a literature search to identify currently available noninvasive techniques that could be used to determine MAP in patients with cf-LVADs, and to find validation studies using invasive intra-arterial blood pressure measurement as a reference to assess validity and success rate.

2 | METHODS

2.1 | Search and study selection

The following three search engines were used: Google Scholar, Scopus, and Pubmed. The search was done in October 2021 for articles containing left ventricular assist device AND blood pressure. Studies were included if patients were supported with a continuous-flow LVAD (Heartware ventricular assist device (HVAD) (Medtronic, Minneapolis, MN), HeartMate II (HMII) (Abbott, Chicago, IL) and HeartMate 3 (HM3) (Abbott, Chicago, IL)). Therefore, a filter was applied, which only selects publications after 2003, the year when the pilot study of the HMII started. HVAD and HM3 devices were developed thereafter. Appendix A contains the search terms and a PICO scheme to describe the search process and the patient population. After screening by title and abstract, reliability, population and data representation of each article was checked. Furthermore, deduplication was performed and articles that did not have intra-arterial blood pressure reference measurements were excluded. The remaining studies that met the requirements were included in this review. A brief technical background of the identified methodologies is provided. The identified methodologies are compared to different clinical uses specifically; ease of operation, operator independence, device availability, cost of device, and out of hospital use. The support of this resulting table is added to Appendix B.

2.2 | Criteria for adequate blood pressure monitoring

The main characteristics of an adequate blood pressure monitor are high validity and a high success rate. The validity examines how accurate the technique is, compared to the gold standard: the A-line. The validity is displayed in different ways between studies. In order to compare the different techniques and their validity, the mean difference (MD) was used. The MD is defined as the mean value for the differences between the technique and the A-line for every patient, with the corresponding standard deviation. MDs smaller than 5 ± 8 mm Hg were considered acceptable, according to the cutoff criteria of the Association for the Advancement of Medical Instrumentation (AAMI).[12] For studies in which the MD was not given, MD was determined on the basis of the figures with dedicated software (WebPlotDigitizer, A.Rohatgi, Pacifica). The validity of the different techniques will be compared in a forest plot. For the success rate, the values are only reported if they are mentioned in the original study. Success rate was defined as the number of the successfully completed measurements divided by the total number of attempted measurements.

3 | RESULTS

3.1 | Search and study selection

The search strategy resulted in 22 091 articles of which 61 articles remained after screening for title and abstract.

After removal of duplicate articles and articles without a complete description of the results, a total of eleven articles were included for this review (Appendix C). These eleven articles were sorted into three blood pressure measurement techniques: Doppler ultrasound, photoplethysmography, and slow cuff deflation devices. Table 1 lists all included studies and their main characteristics.

3.2 | Technical background of non-invasive blood pressure monitors

Non-invasive BP measurement techniques that have been used for the monitoring of patients with cf-LVADs are: Doppler ultrasound, photoplethysmography (pulse oximeter and Nexfin), and slow cuff deflation devices (respectively, Figure 1A–D).

3.3 | Doppler ultrasound

Measuring the BP with Doppler ultrasound is based on the same principle as the auscultatory method, which involves listening to the return of blood flow. To measure blood pressure with Doppler ultrasound, the probe is placed on the radial or brachial artery and a cuff with an analog pressure sensor is placed proximal to the probe on the arm.[13,14] With the sensitive ultrasound probe, the moment of returning flow and maximum flow can be determined while lowering the pressure in the cuff. The rate at

TABLE 1 Included studies

Study	Country	Number of patients	Tested technique	Number of measurements		LVAD type
				Technique	A-line	
Bennet et al. 2010[13]	USA	17	Doppler	144	144	HeartMate II
Lanier et al. 2013[15]	USA	30	Doppler, slow cuff	90[a]	30	HeartMate II
Martina et al. 2014[16]	The Netherlands	31	Nexfin	31[a]	31	HVAD and HeartMate II
Woldendorp et al. 2014[18]	Australia	14	Doppler, pulse oxi	14[a]	14	HVAD
Castagna et al. 2017[10]	USA	30	Slow cuff	90	90	HeartMate II
Hellman et al. 2017[19]	USA	5	Doppler, pulse oxi	8[a]	8	HVAD and HeartMate II
Granegger et al. 2019[14]	Austria	15	Doppler	45	45	HVAD and HeartMate III
Rangasamy et al. 2019[23]	USA	16	Doppler	31[a]	31	HVAD and Heartmate II
Sajgalik et al. 2019[20]	USA	31	Doppler, slow cuff	93[a]	93	HVAD and Heartmate II
Li et al. 2019[22]	USA	154	Doppler	1933	1933	HVAD and HeartMate II
Li et al. 2020[24]	USA	43	Doppler	589	589	Heartmate III

Note: All measurements are reported independent of success.

[a]Same number of measurements per technique.

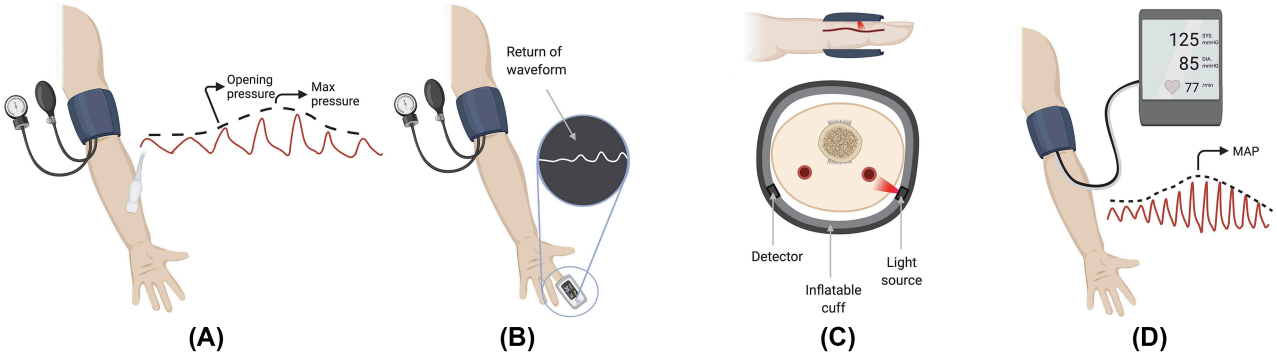

FIGURE 1 (A) Doppler ultrasound, upon cuff deflation, opening pressure and max pressure can be determined with the analog pressure sensor in the cuff, which are related to returning flow and the maximum flow respectively. (B) Pulse oximeter, the pressure in the cuff at the instant of returning pulsatility is assumed to be a measure of MAP. The pressure is measured with the analog pressure sensor present in the cuff. (C) Nexfin, the pressure in the cuff is controlled to keep the plethysmogram fixed at a certain setpoint. The cuff pressure reflects the arterial pressure in shape and in value. (D) Slow-cuff, the oscillogram obtained during deflation is analyzed to determine MAP.

which the pressure should be lowered is about 2–3 mm Hg per second.[15] The sensitive probe in combination with the slow cuff deflation is thought to increase the accuracy of blood pressure measurement in cf-LVAD patients compared to traditional BP cuff measurements.

3.4 | Photoplethysmography

The photoplethysmography technique uses a light source and a detector to determine the blood volume. The light source illuminates the finger and the detector captures a certain amount of light on the other side. The amount of light captured is related to the blood volume in that particular body part. Despite the fact that the pulsation is less for patients with a cf-LVAD, a plethysmogram can be created. It is hypothesized that the use of light to measure small blood volume differences, is an accurate method to measure the blood pressure in comparison to traditional BP cuff measurements. There are two techniques that use photoplethysmography to monitor blood pressure on cf-LVAD patients: the pulse oximeter and the Nexfin (BMEYE B.V., The Netherlands).[16–19]

3.4.1 | Pulse oximeter

A standard pulse oximeter can show the waveform of the blood pressure. It has to be combined with a cuff with an analog pressure sensor around the wrist or upper arm. When the pressure in the cuff is decreased, the waveform appears and becomes more prominent. Literature suggests the pressure at which a significant signal can be seen, corresponds with the MAP.[18,19]

3.4.2 | Nexfin

A more advanced method of using photoplethysmography is applied in the Nexfin. A cuff is placed around the finger and by balancing arterial pressure with the cuff pressure, using a fast control system, the diameter of the artery is kept constant. The pressure waveform in the cuff is therefore related to the pressure waveform in the artery, which can be converted to a MAP.

3.5 | Slow cuff deflation device (slow-cuff)

Automated oscillometric BP monitors use air pressure in the cuff to determine the blood pressure. The lower pulsatility in cf-LVAD patients results in smaller oscillations in the cuff which are harder to measure. To assess these oscillations more accurately, various devices use a cuff which depressurizes at least two times slower than the normal oscillometric devices. This makes it easier to filter the oscillometric pressure waves from the descending pressure–time curve compared to standard oscillometric BP monitors. Three slow cuff-deflation devices have been clinically tested on cf-LVAD patients.[10,15,20]

3.5.1 | Terumo Elemano

The Terumo Elemano BP (Terumo Corporation, Tokyo, Japan) uses a double cuff system, which consists of a bigger cuff and a smaller cuff in the middle.[21] The arterial blood flow is cut off by the bigger cuff, and the pulsatility of the blood is measured by the smaller cuff. The advantage of the smaller cuff is that it does not rest against an artery, so there is no background pulsation when the cuff is inflated above systolic pressure.

3.5.2 | Mobil-O-Graph

The Mobil-O-Graph (IEM, Stolberg, Germany) uses a proprietary algorithm to determine the SBP, DBP and MAP. The Mobil-O-Graph is designed for ambulatory blood pressure monitoring and therefore focuses mainly on comfort while taking measurements.

3.5.3 | ExpBP

The ExpBP (experimental device) is an automatic slow cuff-deflation device specifically designed for the cf-LVAD population.[20] It uses customized software to accommodate for lower blood pressure pulsatility. The SBP and DBP are obtained using specific criteria for the magnitude of the oscillometric waveform.

3.6 | Clinical usability—Potential advantages and disadvantages

Each of the methodologies for non-invasive blood pressure monitoring devices reviewed above comes with specific advantages and disadvantages, an overview is given in Table 2 for different clinical uses.

Not every technique mentioned above has presently a high clinical usability. For example, only one of the slow-cuffs, the Mobil-O-Graph, is currently commercially available. The ExpBP is still in development and therefore not ready for clinical implementation. The Terumo Elemano

TABLE 2 Clinical usability, potential advantages and disadvantages

Technique	Ease of operation	Operator independence	Device availability	Cost of device	Out of hospital use
Doppler	−	−−	++	+	−−
Pulse oximeter	+	−	++	++	+
Nexfin	+	+	−−	−−	−−
Slow cuff[a]	++	++	−	+	++

Note: Clinical use is rated poor (−−), moderately poor (−), good (+), or excellent (++). Ease of operation is based on the skill an operator requires. Operator independence shows the need for an operator. Device availability represents the accessibility of devices in hospital. Cost is based on in hospital use. Out of hospital use is based on potential home implementation.

[a]Based on the average of the devices.

has been implemented in some clinics, but due to the discontinuation of production, no new devices are available. For this reason, widespread usability in clinics would be difficult. While pulse oximeters are abundantly present in clinics, this method of measuring the MAP has only been studied but not implemented in clinical practice. Due to the cost, Nexfin and its successors have not yet been implemented for cf-LVAD patients. In contrast, Doppler is increasingly adopted for clinical measurements.[22]

4 | VALIDITY

The validity results per study are summarized in Table 3 and visualized in Figure 2.

4.1 | Doppler ultrasound

The included articles provided nine studies with ten MDs for MAP determined with Doppler in comparison to the A-line. Not all the studies used the same way to determine the MAP; six studies used the opening pressure to determine the MAP[13,15,20,22–24] and two studies used the maximum flow.[14,19] Woldendorp et al. did not mention a specific Doppler measurement protocol.[18] For all the included studies, the MD ranged from −2.1 to +10.5 mm Hg. The found correlation coefficients for Doppler ranged from $r = 0.42$ ($p < 0.05$) up to $r = 0.87$ ($p < 0.05$). Doppler demonstrated a high success rate ranging from 71% to 100%. In five studies the success rate was not reported.[18,19,22–24]

4.2 | Photoplethysmography

Two studies looked at the possibilities of using pulse oximetry for the measurement of blood pressure. The study by Woldendorp et al. stated an MD of 3.2 ± 7.9 mm Hg,[18] while the study by Hellman et al. gave a MD of 0.1 mm Hg (95%CI: −1.5; 1.6), which translated to a SD of 1.7 mm Hg.[19] Woldendorp et al. calculated a correlation coefficient of $r = 0.64$ ($p < 0.0016$) for the relation between A-line and the pulse oximeter.[18]

The validity and success rate of the Nexfin (BMEYE B.V., Amsterdam, The Netherlands) on patients with a cf-LVAD was tested in a study by Martina et al. from 2014.[16] The described MD was −6.9 ± 5.1 mm Hg. Besides the MD, the correlation coefficient for the relation between the A-line and the Nexfin was determined, showing an $r = 0.76$ (95% BI: 0.54; 0.82). The success rate of the measurements was 93%.

4.3 | Slow cuff

The included articles had three studies examining three different "slow cuff" methods: Terumo Elemano (Terumo Corporation, Tokyo, Japan), Mobil-O-Graph (IEM, Stolberg, Germany), and the ExpBP (experimental device). For the Terumo, for patients with a cf-LVAD, the MD of the MAP was 1.7 ± 8.3 mm Hg and the correlation coefficient of $r = 0.75$ ($p < 0.0001$).[15] In addition, a success rate of 88% was found in cf-LVAD patients. The Mobil-O-Graph had an MD of 2.4 ± 4.5 mm Hg with a correlation coefficient of $r = 0.87$ ($p < 0.001$).[9] The success rate was 82%. The MD of the ExpBP was determined to be 1.2 ± 4.8 mm Hg.[20] In addition, the ExpBP had a correlation coefficient of $r = 0.84$ ($p < 0.01$). This device had a success rate of 95% for the MAP.

The acceptance criteria of the Association for the Advancement of Medical Instrumentation (AAMI) states the error of the MAP should be within ±5 mm Hg with a SD of below 8 mm Hg.[12] All weighted averages of the different techniques satisfy this criterion except the Nexfin.

5 | DISCUSSION

In this review, we assessed the validity and the success rate of techniques that could be used for measuring BP in

TABLE 3 Data of included articles

Technique	Article	MD	SD (of MD)	SR	*r*	*n*
Doppler	Bennet et al. 2010[13]	0.2	±10.5	94%	0.76	144
	Lanier et al. 2013[15]	9.5	±1.9	100%	0.64	90
	Woldendorp et al. 2014[18]	4	±9.0	–	0.63	14
	Hellman et al. 2017[19]	4.1	±9.6	100%	–	8
	Granegger et al. 2019[14]	−2.1	±7.3	71%	–	45
	Rangasamy et al. 2019[23] (pulsatile)	10.0[a]	±9.3[a]	–	0.42	18
	Rangasamy et al. 2019[23] (nonpulsatile)	5.0[a]	±3.8[a]	–	0.87	13
	Sajgalik et al. 2019[20]	6.7	±5.2	99%	0.82	93
	Li et al. 2019[22]	2.4	±7.5	99%	0.74	1933
	Li et al. 2020[24]	2	±7.3	99%	0.75	589
	SD (unweighted)	**±3.8**	**±2.7**	**±10.6%**	**±0.14**	
	Mean (weighted)	**2.6**	**±7.4**	**97%**	**0.73**	
Pulse oximeter	Woldendorp et al. 2014[18]	3.2	±7.9	86%	0.64	14
	Hellman et al. 2017[19]	0.1	±1.7	88%	–	8
	SD (unweighted)	**±2.2**	**±4.4**	**±1.4**	**–**	
	Mean (weighted)	**2.2**	**±5.8**	**87%**	**0.64**	
Nexfin	Martina et al. 2014[16]	−6.9	±5.1	93%	0.76	31
	SD (unweighted)	**–**	**–**	**–**	**–**	
	Mean (weighted)	**−6.9**	**±5.1**	**93%**	**0.76**	
Slow cuff	Lanier et al. 2013[15]	−1.7	±8.3	91%	0.75	30
	Castagna et al. 2017[10]	2.4	±4.5	82%	0.87	90
	Sajgalik et al. 2019[20]	1.2	±4.8	95%	0.87	93
	SD (unweighted)	**±2.1**	**±2.1**	**±7.7%**	**±0.07**	
	Mean (weighted)	**1.3**	**±5.2**	**89%**	**0.85**	

Note: The total mean difference (MD), standard deviation (SD) and success rate (SR) for each technique are weighted means based on the number of successful measurements. r = coefficient of correlation, n = total number of measurements.

[a]The MDs and SDs were extracted from the figures with WebPlotDigitizer.

patients on cf-LVAD support. The most important findings are that the validity of slow cuff measurements is highest, while that of Nexfin is lowest. The highest mean success rate was found for the Nexfin and the lowest success rate was found for the pulse oximeter. Slow cuff devices scored best in the clinical use comparison. One of the reasons for the observed high validity in slow cuff devices might be the fact that these devices run on algorithms that have been extensively verified. In addition, the slow deflation of the cuffs enables them to measure very small differences in pressure making them suitable for measuring blood pressure in cf-LVAD patients.

However, only one of the slow-cuff devices is available on the market and three studies have been performed with a relatively low number of measurements compared to the studies for the Doppler technique. The study by Li et al. was performed prospectively and blinded to the timing of invasive MAP by arterial line, making the Doppler correlation perhaps more scientifically robust. There were no exclusion criteria, and the study population included any LVAD patient who required an arterial line, minimizing the risk of selection bias. Given the fact that all LVAD patients were included, it seems plausible that the Doppler method is reliable for the majority of LVAD patients across the continuum.

Several reasons for the lower validity of the other techniques can be identified. For Doppler, it is still unclear how the MAP may be accurately determined. Six studies use the pressure corresponding with the first flow after artery opening for a MAP measurement,[11,14,20–23] While two studies use the pressure corresponding with the maximum flow in the artery.[18,19] The results from both methods are not far apart, which makes it difficult to establish which method is better.

Both pulse oximetry and Nexfin depend on measuring the volume of blood in the finger. Vessels in the fingers are quite small and are prone to vasoconstriction and vasodilation. This makes their MDs susceptible to variability. Another factor that could influence the validity in photoplethysmographic devices is whether the aortic valve is

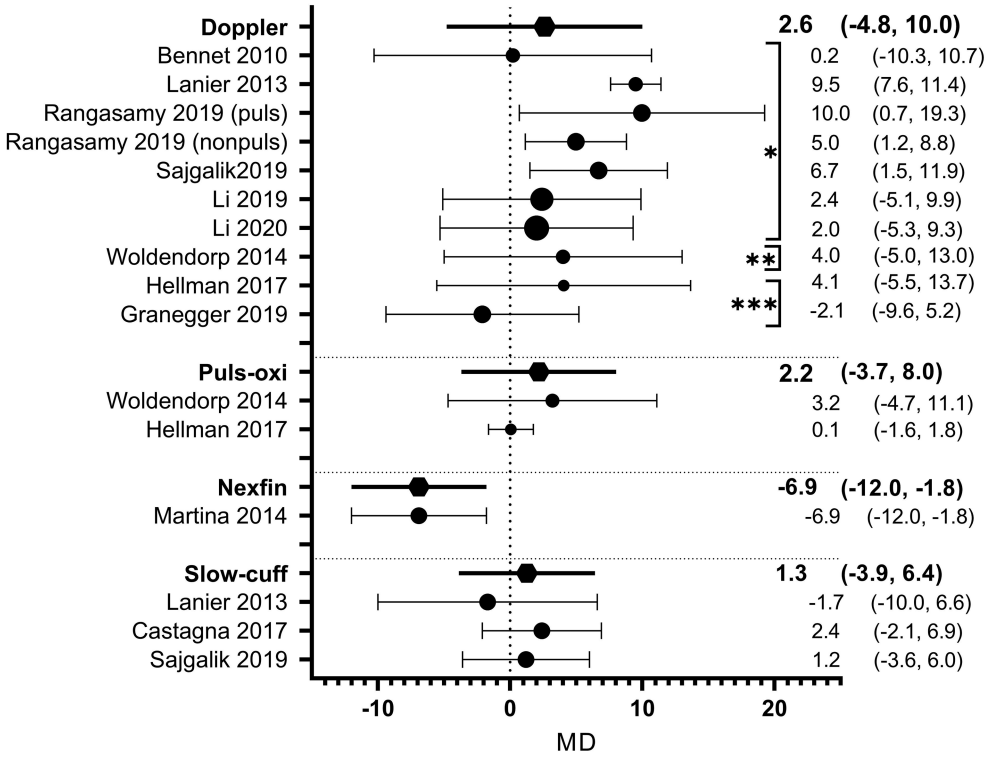

FIGURE 2 Forest plot of the validity. The mean difference (MD) is defined as the mean value for the differences between the tested technique and invasively measured arterial pressure for every patient, with the corresponding standard deviation. For each technique a weighted average MD is calculated with corresponding standard deviation. *Used "opening pressure" (see text) for mean arterial pressure (MAP), **unknown doppler method, ***used "max flow" for MAP (see text).

opening with a heartbeat or remains closed. With an open aortic valve the difference between the MAP and the SBP is difficult to determine and with a closed aortic valve the MAP is often overestimated.[18]

The arterial pulsatility in patients with a cf-LVAD depends on the level of support and the residual ventricular activity of the patient.[14] The remaining pulsatility can affect the validity of the BP monitors. The described effects of pulsatility on Doppler measurements are divergent in the various studies that are considered in this review. Here we split the results from the study done by Rangasamy et al. into pulsatile and nonpulsatile patients. This is done because Rangasamy et al. found that Doppler blood pressure measurements are less accurate for pulsatile patients in comparison to nonpulsatile patients. Most other Doppler studies confirm this finding.[20,22,24,25] Sajgalik et al. state that it can cause overmedication with antihypertensive therapy.[20] Li et al. however claim that this measurement difference pulsality or a palpable pulse does not affect measurement accuracy and therefore has no clinical relevance.[22] In addition to Doppler, a low pulsatility can have an effect on plethysmographic measurements. Woldendorp et al. found that it is difficult to determine plethysmographic waveforms in case of low pulsatility in a patient.[18] Martina et al. also state that a low pulsatility can lead to measurement artifacts.[17] However, this was only observed in a patient during cardiopulmonary bypass and not in patients on cf-LVAD support. Pulse pressures higher than 5 mm Hg seem to be well within the range of measurements of the Nexfin monitor. In the studies on slow-cuff devices, no mention is made about the influence of pulsatility on the quality of the BP measurements.

The success rates in different studies of the same techniques are variable. Doppler had success rates ranging from 71% to 100%. This range is probably due to the difference in definition of success and the difference in measurement settings. Pulse oximetry and Nexfin may be affected by the placement of the probe on the finger or patient-specific characteristics like the state of the vessels. Reported success rates were 86% for pulse oximetry and 93% for the Nexfin. The slow cuff devices have a variable success rate with the highest being 95% and the lowest being 82%. This can be attributed to the different devices that were used and their different settings. The success rates for slow cuff devices are affected by the low pulsatility of the cf-LVAD patients. It can be concluded that it is difficult to interpret the success rates and therefore it is problematic to comment on these results. However, all techniques seem to have acceptable success rates.

Some limitations of this study need to be discussed. The field of research on blood pressure monitors for cf-LVAD patients is small and therefore the number of studies is limited. Moreover, research into the influence of blood pressure on cf-LVAD patients is just emerging, because only recently the cf-LVADs last longer in vivo and blood pressure related problems are becoming more relevant.[24] As a result, only a few studies can be found per technique. In addition, the studies found do not comply with international protocols for validation or do not publish the necessary results. A recent study by Cohen et al. mentioned that less than 15% of the commercially available automatic BP monitors comply with standard testing to ensure validity. These standards include listing the age of participants and the cuff size used.[26] The validity is reported in different ways within the studies, making any comparison difficult. Due to the lack of access to individual study data there was no possibility to check for statistical significance. However, methods were considered acceptable when results were within the cutoff criteria of the AAMI so that clinically relevant conclusions can be drawn.[12]

In this review, the choice was made to compare the techniques in terms of validity based on MD and correlation coefficient. When drawing conclusions, we also take the number of performed measurements into account. The MD was not given for the research by Rangasamy et al. and therefore had to be derived from the figures with WebPlotDigitizer.[23] This process could cause deviations from the original MD, making these values less reliable. Additionally, not every study reported a success rate and not every study stated clearly when a measurement was considered successful. This makes it difficult to draw conclusions on the differences between the investigated techniques. Some of the techniques were studied by their developers. This is the case for the Doppler wristband, Nexfin monitor and the ExpBP. The results may therefore be biased and there are no independent studies validating these results.

Only 3 studies mention the methods used for A-line measurements and no studies examine the accuracy of the A-line measurements. Gardner et al. have explored the ways in which A-line measurements can be inaccurate and how this can be avoided.[27] Although most clinicians have standardized protocols to assure accurate A-line measurements, the adequacy of the A-line measurements is not discussed.

The baseline characteristics differ between studies (mean age 41.2–63 and male 60%–100%). In addition, not all studies mention factors that could influence the BP measurements e.g. vasoactive medication. This does not necessarily mean that the studies are not comparable. The advantage of the study design is that the patient is its own control.

The rating system for the potential advantages and disadvantages is based on in-house experience and might differentiate from other centers. Appendix B is added to support the rating process.

A technique that has been omitted from this review is tonometry. This technique is described as a noninvasive blood pressure monitor for patients with a cf-LVAD by Zayat et al.[25] In this study, the tonometer (the DMP-Life, Daeyomedi Co., Ltd., Gyeonggi-do, South Korea) was compared with doppler instead of the A-line in cf-LVAD patients. For this reason, this study was excluded. It was shown in multiple studies that the Doppler technique slightly overestimates the intra-arterial MAP. By comparing the DMP-life SBP to the Doppler opening pressure, an overestimation may be expected. Therefore, a measurement with the DMP-life could give a better representation of actual SBP than the research suggests.[28] This technique could be promising in the future, hence its potential merits are being mentioned here.

Recently Alvarez et al. published a review on noninvasive blood pressure monitors.[29] They proposed an algorithm with Doppler and automatic blood pressure measurements after reviewing different noninvasive blood devices in multiple studies. Alvarez et al. focused mainly on the correlation coefficient of the techniques with the A-line.[30] We chose to compare the results directly with a shared validity standard, the mean difference with the A-line as reference, in combination with the acceptance criteria of the AAMI. In addition, a technical background was provided to offer understanding of each technique and therefore a better insight into the potential of each technique. Our different approach to reviewing the noninvasive blood pressure measurement techniques provides alternative conclusions and future perspectives.

6 | CONCLUSION

The Nexfin and pulse oximeter both use plethysmography, but the Nexfin underestimated the MAP while the pulse oximeter overestimated the MAP. The slow cuff methods have shown the lowest mean difference, falling within AAMI criteria while having a success rate of 90%. While the results are promising, no multicenter prospective data is available and only one of the slow cuffs is commercially accessible. Doppler is a technique that has been extensively investigated, and although the success rate is high, the validity varies between studies. Nevertheless, the Doppler method could be considered the standard of care in health care settings because of its widespread availability and reliability. With further development, a slow-cuff device has the potential to become a reliable and quick method to replace Doppler and assess the blood pressure

of cf-LVAD patients in clinic, or in the future even in a home setting.

AUTHOR CONTRIBUTIONS

Steven Lankheet, Martijn M. Pieterse, Robin Rijnhout, Emma Tuerlings: Concept/design, Data collection, Data analysis/interpretation, Drafting article, Critical revision of article, Approval of article; Anne-Marie C. Oppelaar, Linda W. van Laake, Faiz Z. Ramjankhan: Critical revision of article, Approval of article; Berend E. Westerhof and Marish I. F. J. Oerlemans: Concept/design, Drafting article, Critical revision of article, Approval of article.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest with the contents of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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