Comparison Study of Central Blood Pressure and Wave Reflection Obtained From Tonometry-Based Devices

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BACKGROUND
Although tonometry-based devices have been applied in several population studies and clinical trials, the agreement between them remains unclear.

METHODS
Carotid systolic blood pressure (SBP) and augmentation index (AI) were randomly measured from 3 devices, SphygmoCor, PulsePen, and A-Pulse, in 66 consecutive patients from our ambulatory cardiovascular department. The study contains 2 phases: in Study 1, SphygmoCor and PulsePen were performed on each participant by 2 experienced physicians (n = 66); in Study 2, A-Pulse was added after the measurements of SphygmoCor and PulsePen and performed by another technician on the last 34 patients.

RESULTS
Carotid SBP and AI measured by the 3 devices were strongly correlated (R ≥ 0.78; P < 0.001), but with significant discrepancies. Specifically, in 66 participants of Study 1, PulsePen estimated higher carotid SBP and AI by 5 mm Hg and 5.7%, respectively, than SphygmoCor. In 34 patients of Study 2, A-Pulse estimated higher central SBP by 3.7 mm Hg than SphygmoCor, and lower central SBP by 5.7 mm Hg than PulsePen. However, no significant difference in interclass comparison was detected between the 3 devices (P ≥ 0.26). Furthermore, slopes of correlation plots of parameters between SphygmoCor and PulsePen were not significantly different from 1 (P ≥ 0.09), but were different in the case of A-Pulse (P ≤ 0.004).

CONCLUSIONS
Tonometry-based devices were not consistent in measurements of central BP and wave reflections in clinical practice, with considerable and significant differences among them. However, in contrast to A-Pulse, SphygmoCor and PulsePen can probably assess similar cardiovascular risk for individuals, with a systematical discrepancy.

Keywords: augmentation index; blood pressure; central systolic blood pressure; hypertension; tonometry.

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In recent years, several indexes of arterial stiffness or wave reflections have been considered as independent predictors of cardiovascular (CV) or all-cause mortality in various populations.1–3 Pulse wave velocity, as a gold standard of arterial stiffness, has been recommended by the European Society of Hypertension and the European Society of Cardiology as a clinical marker for CV risk stratification in subjects with hypertension.4 More recently, indexes of wave reflections have been introduced into hypertensive practice, contributing to the increased complexity of stratification of CV risk in this population. Regarding measurements of not only wave reflections but also of central blood pressure (BP), several debates have been noted in the evaluation of predictive value of such parameters.5–7 Many of them seem to be highly influenced by the quality and the heterogeneity of the chosen devices.

It is now important in evaluating arterial stiffness and wave reflections to develop noninvasive devices issued from tonometry, oscillometry, and other methodologies, which could be easily applied in clinical practice and research. In the last decade, many devices have been compared with each other, or validated by invasive measurement.8–16 In literature, SphygmoCor (AtCor Medical, Sydney, Australia) and PulsePen (DiaTecne s.r.l., Milan, Italy) were separately compared with invasive measurement and Complior System (Colson, Paris, France).8–12 It seems that tonometry...
is the most accurate noninvasive methodology in the field of hemodynamic measurement. However, SphygmoCor and PulsePen, the two broadly used tonometry-based devices, have never been compared, and agreement as to accuracy remains unclear. Given the fact that these devices have been applied in the past, mostly for pulse wave velocity measurements in several population studies and clinical trials, a comparison between them is undoubtedly necessary but should be mainly focused on measurements of central BP and wave reflections.

Accordingly, a comparison study was conducted on 66 inpatients from our ambulatory CV department. Our study contains two sections: first, SphygmoCor and PulsePen were compared directly with each other with regard to central BP and wave reflections; second, A-Pulse, a novel tonometry-based device, was compared to SphygmoCor and PulsePen, separately, in the last 34 patients of all participants. Our goal is to assess the agreement between these tonometers.

METHODS

Study Participants

In the present study, a total of 68 consecutive inpatients, aged 20 to 84 years, were recruited from the ambulatory CV department of Hotel-Dieu Hospital, Paris, France. All patients were referred for a CV evaluation in the context of presence of at least one CV risk factor. Inclusion criteria was atrial fibrillation and severe heart failure (New York Heart Association classification III–IV). Informed consent was obtained from all participants. Clinical documents were reviewed to define the CV diseases and therapies. The Ethics Committee of Hotel-Dieu Hospital approved the study protocol.

Anthropometric Measurement

Body height, body weight, and waist and hip circumferences were measured, and body mass index was calculated by dividing body weight in kg by the squared body height in meters.

Blood Pressure Measurements

All measurements of the hemodynamic parameters were performed in the supine position after at least 5 minutes of rest. Brachial BP was recorded twice by a validated oscillometric device (SCVL, Paris, France) just prior to the use of each device. Averaged BPs were used for further analysis and calibration of the obtained pressure waveforms from each device.

Study Design

In 66 participants of Study 1, measurements of SphygmoCor and PulsePen were randomized in sequence and performed at a single visit by two experienced physicians, and each one was assigned to operate exclusively on 1 device. In Study 2, A-Pulse measurement was added in the last 34 patients, in a nonrandomized order, and always after the measurements with SphygmoCor and PulsePen.

Applied Principles for Central BP Assessment With Each Device

The SphygmoCor device can perform carotid and aortic pulse wave analysis. Specifically, the carotid waveform can be directly recorded by applanation tonometry and calibrated with peripheral diastolic and mean BPs in order to provide the carotid BP. The peripheral diastolic and mean BPs were calculated with the radial area-under-the-curve method. The radial waveform was calibrated via brachial systolic and diastolic BPs. The aortic BP can be assessed with the application of a generalized transfer function, which transformed the radial pressure waveform to aortic pressure waveform. However, since PulsePen cannot estimate aortic BP with a transfer function, aortic BP was not compared between the 2 devices.

PulsePen can provide pulse wave analysis assessment of several arterial sites, including carotid, radial, and femoral arteries, with a high-fidelity applanation tonometer. At each site (e.g., carotid) of waveform, the local pressure can be assessed by calibrating the waveform with peripheral diastolic and mean BPs. The manual reanalysis of the peak of pressure waveform, with assistance of the multidimensional derivative, is available with the inbuilt PulsePen software. More details regarding the PulsePen device are available in a previous publication.

A-Pulse CASPro (HealthSTATS, Singapore) is a noninvasive device based on tonometry, which is used to obtain central systolic blood pressure (SBP) and radial augmentation index (AI) through radial pressure waveform recording. The device comprises a watch-like wrist sensor to capture the radial waveform, a brachial blood pressure cuff to record systolic and diastolic BPs, and a monitor. The wrist sensor captured the radial waveform, which was calibrated by the averaged brachial systolic and diastolic BPs. Then, the algorithm of inbuilt software calculated central SBP and radial AI.

Calculations on AI and Form Factor

Radial (rAI) and carotid augmentation index (cAI) were calculated automatically by the inbuilt software of each device, with the following formula: $rAI (%) = \frac{\text{first peak BP}}{\text{pulse pressure} \times 100}$; and $cAI (%) = \frac{\text{(pulse pressure - first peak BP)}}{\text{pulse pressure} \times 100}$. Radial and carotid form factors (FFs) were calculated as follows: $FF (%) = \frac{\text{mean BP - diastolic BP}}{\text{pulse pressure} \times 100}$.

Statistics

Quantitative and qualitative parameters were presented as means ± SD and numbers with percentages in parenthesis, respectively. We applied the student $t$ test to assess the absolute differences in hemodynamic parameters vs. zero, and paired $t$ test to perform interclass comparison between two devices. Correlations of hemodynamic parameters, as well as their means and differences, were studied.
by Pearson correlation coefficient, Bland-Altman plot, and intraclass correlation coefficient. Stepwise multivariate linear regression was used to investigate factors associated to parametric variations, with covariables as age, gender, body weight, body height, heart rate, mean BP difference in radial and carotid FFs, as well as the mean carotid systolic BP or AI. The Z test was applied to compare slopes of correlation plots with 1. Statistical analysis was performed using SAS software, version 9.1 (SAS Institute, Cary, NC). A $P$ value $<0.05$ was considered statistically significant.

**RESULTS**

**Participants**

The present study recruited 68 participants (mean age ± SD: $59.5 ± 15.7$ years), of whom the last 34 patients participated in Study 2. Two subjects were excluded from statistical analysis for the poor quality of tonometric signal. Table 1 shows the characteristics of all participants, and there is no significant difference between subjects in Study 1 ($n = 66$) and Study 2 ($n = 34$).

**Study 1: SphygmoCor vs. PulsePen**

As shown in Table 2, between SphygmoCor and PulsePen, there was no significant difference in brachial BP and heart rate, which were measured before tonometry. Moreover, in the interclass comparison, no significant difference in carotid SBP and AI was observed between SphygmoCor and PulsePen. Indeed, compared to SphygmoCor, PulsePen estimated higher carotid SBP and AI by $5$ mm Hg and $5.7\%$, respectively ($P < 0.001$ for both). For radial and carotid FFs between the two devices, difference in interclass comparison and absolute differences all reached statistical significance ($P < 0.001$ for all).

Figure 1 indicates that carotid SBP and AI measured by SphygmoCor and PulsePen were strongly correlated ($R ≥ 0.86$; $P < 0.001$). On Bland-Altman analysis, no significant association between mean value and difference of these measurements was observed ($P ≥ 0.48$). Furthermore, the slopes of the correlation plots between all the hemodynamic parameters determined by the two devices were $0.90$, and were not significantly different from $1$ ($P ≥ 0.09$).

According to the intraclass correlation coefficient test, intraclass correlation coefficients between measurements obtained by SphygmoCor and PulsePen were $0.84$ and $0.87$ for carotid SBP and carotid AI, respectively. These coefficients reached statistical significance in the subsequent $F$ test ($P < 0.001$ for all).

Determinants of discrepancies in hemodynamic parameters between SphygmoCor and PulsePen were assessed (Table 3). Carotid and radial FFs and body weight explained $41\%$ of variance in the carotid SBP model, and carotid FF was the only factor to explain the variation of carotid AI between

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**Table 1.** Characteristics of participants ($n = 68$)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>$59.5 ± 15.7$</td>
</tr>
<tr>
<td>Male gender, n (%)</td>
<td>$41 (61.3)$</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>$28.1 ± 5.1$</td>
</tr>
<tr>
<td>Smoker, n (%)</td>
<td>$23 (33.8)$</td>
</tr>
<tr>
<td>Hypertension, n (%)</td>
<td>$49 (72.1)$</td>
</tr>
<tr>
<td>Diabetes, n (%)</td>
<td>$13 (19.1)$</td>
</tr>
<tr>
<td>Dyslipidemia, n (%)</td>
<td>$26 (38.2)$</td>
</tr>
<tr>
<td>Antihypertensive therapy, n (%)</td>
<td>$47 (73.4)$</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD. Clinical documents were reviewed to define the cardiovascular diseases and therapies.

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**Table 2.** Comparison of carotid SBP and AI measured by SphygmoCor and PulsePen ($n = 66$)

<table>
<thead>
<tr>
<th></th>
<th>PulsePen</th>
<th>SphygmoCor</th>
<th>$P$ for interclass comparison$^a$</th>
<th>Absolute difference (PulsePen – SphygmoCor)</th>
<th>$P$ for absolute difference$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood pressure monitor before tonometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic BP, mmHg</td>
<td>$135 ± 18$</td>
<td>$136 ± 16$</td>
<td>$0.65$</td>
<td>$1.3 (-0.8, 3.5)$</td>
<td>$0.22$</td>
</tr>
<tr>
<td>Diastolic BP, mmHg</td>
<td>$80 ± 12$</td>
<td>$80 ± 11$</td>
<td>$0.73$</td>
<td>$0.5 (-0.9, 1.9)$</td>
<td>$0.46$</td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>$66 ± 14$</td>
<td>$66 ± 13$</td>
<td>$0.84$</td>
<td>$0.8 (-0.5, 2.2)$</td>
<td>$0.23$</td>
</tr>
<tr>
<td>Pulse wave analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carotid systolic BP, mmHg</td>
<td>$130 ± 20$</td>
<td>$126 ± 19$</td>
<td>$0.16$</td>
<td>$5.0 (2.5, 7.5)$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Carotid AI, %</td>
<td>$15.9 ± 22.3$</td>
<td>$10.9 ± 22.2$</td>
<td>$0.21$</td>
<td>$5.7 (3.1, 8.3)$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>FF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carotid FF, %</td>
<td>$43.7 ± 3.9$</td>
<td>$40.8 ± 3.9$</td>
<td>$&lt;0.001$</td>
<td>$2.9 (2.1, 3.7)$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>Radial FF, %</td>
<td>$38.6 ± 3.9$</td>
<td>$33.3 ± 3.9$</td>
<td>$&lt;0.001$</td>
<td>$5.1 (4.3, 6.0)$</td>
<td>$&lt;0.001$</td>
</tr>
</tbody>
</table>

Values are means ± SD and absolute differences with 95% confidential intervals in parenthesis. FF = (mean BP – diastolic BP) / pulse pressure.

Abbreviations: AI, augmentation index; BP, blood pressure; bpm, beats per min.; FF, form factor.

$^a$P value for interclass comparison between PulsePen and SphygmoCor.

$^b$P value for absolute difference between PulsePen and SphygmoCor vs. zero.
the two devices. Forward and backward multivariate linear regression models were also applied to select the determinants of the discrepancies, and our finding remained unaltered.

**Study 2: A-Pulse vs. SphygmoCor and PulsePen**

In Table 4, brachial BP measured by A-Pulse before tonometry did not differ significantly from that measured by SphygmoCor or PulsePen \((P \geq 0.06)\). Although there was no significant difference in central SBP between A-Pulse and SphygmoCor or PulsePen in the interclass comparison \((P \geq 0.09)\), their absolute differences all reached statistical significance \((P \leq 0.03)\). Specifically, A-Pulse estimated higher central SBP than SphygmoCor carotid SBP by 3.7 mm Hg, and lower central SBP than PulsePen carotid SBP by 5.7 mm Hg. However, neither interclass comparison nor absolute difference in radial AI was significant between the three devices \((P \geq 0.09)\).

As shown in Figure 2, A-Pulse central SBP closely correlated with carotid SBP from SphygmoCor and PulsePen \((R \geq 0.78, P < 0.001)\). On Bland-Altman analysis, the differences
in central SBP did not significantly correlate with the corresponding mean values, except for the values calculated when A-Pulse and PulsePen were compared ($P = 0.02$). Moreover, slopes of correlation plots between A-Pulse and SphygmoCor or PulsePen were significantly different from 1 ($P \leq 0.004$).

**DISCUSSION**

In the present study, we assessed the discrepancy between 3 tonometry-based devices in 66 patients, and focused on parameters of central BP and wave reflection. Two major findings were obtained: (i) although hemodynamic measurements correlated well between the 3 devices, considerable and significant discrepancies were detected; (ii) when hemodynamic parameters were compared between SphygmoCor and PulsePen, slopes of correlation plots were not significantly different from 1, indicating that only systematic discrepancies existed between the two devices, but were different in the case of A-Pulse.

**Comparison Between SphygmoCor and PulsePen**

In most comparison studies concerning pulse wave analysis, a strong correlation of carotid AI from different devices were frequently reported, but with a substantial absolute difference, mainly due to the different methodologies used. However, even with the same methodology, we observed an absolute difference of 5.7 ± 10.2% between SphygmoCor and PulsePen, and found that carotid FF, an indicator of the morphology of carotid pressure waveform, was the only determinant of this disparity. Besides, the reflected point of carotid waveform was determined by 4th derivative in PulsePen, but by 2nd or 3rd derivative in SphygmoCor, which could be another potential explanation of the observed discrepancy.

Comparison studies of carotid SBP among devices are scarce in the literature. In a recent study, when SphygmoCor was compared with Omron HEM-9000AI, a semiautomated tonometry device, Richardson *et al.* revealed that estimated aortic SBP was 12.2 ± 4.6 mm Hg higher in Omron than that in SphygmoCor. In the present study, we also observed a higher carotid SBP from PulsePen as compared with SphygmoCor. In the regression model, we noted that body weight, as well as differences in radial and carotid FFs between the two devices, accounted for 41% of the variance of the observed discrepancy. Because tonometry was the only methodology applied, it was unexpected to find that the FFs were significantly different between SphygmoCor and PulsePen at both radial and carotid sites. To our knowledge, the potential explanations include the different constructional design of the probes, such as the different transducer and sample frequency (128 Hz in SphygmoCor and 500 Hz in PulsePen). In addition, although the BP and heart rate

| Table 3. Determinants of differences in carotid SBP and AI obtained by SphygmoCor and PulsePen (n = 66) |
|---------------------------------------------------|------------|-------------|----------|
| Determinants of difference in carotid SBP         | β ± SE      | Partial R²  | P        |
| Difference of carotid FF, %                       | –1.35 ± 0.34 | 0.16        | 0.004    |
| Difference of radial FF, %                        | 1.16 ± 0.33  | 0.16        | 0.001    |
| Body weight, kg                                   | 0.18 ± 0.09  | 0.09        | 0.01     |
| Determinants of difference of carotid AI          | Difference of carotid FF, % | 0.99 ± 0.45 | 0.09 | 0.03 |

In each model, the stepwise multivariate linear regression was conducted with covariables as age, gender, body weight, body height, heart rate, mean BP, difference in radial and carotid FF, as well as the mean carotid SBP or AI. FF = (mean BP – diastolic BP) / pulse pressure. All difference values indicate the value of PulsePen minus that of SphygmoCor.

Abbreviations: AI, augmentation index; BP, blood pressure; FF, form factor; SBP, systolic blood pressure.

| Table 4. Comparison of carotid SBP and radial AI between reference device (SphygmoCor and PulsePen) and A-Pulse (n = 34) |
|---------------------------------------------------|------------|-------------|----------|
| BP monitor before tonometry                        | Reference  | A-Pulse     | P for interclass comparison¹ | Absolute difference (A-Pulse – reference) | P for absolute difference² |
| SphygmoCor systolic BP, mm Hg                      | 128 ± 14   | 0.41        | 2.7 (–0.1, 5.4) | 0.06 |
| PulsePen systolic BP, mm Hg                        | 128 ± 12   | 130 ± 13    | 0.55      | 1.8 (–0.1, 3.7) | 0.06 |
| SphygmoCor diastolic BP, mm Hg                     | 78 ± 10    | 0.61        | –1.2 (–3.4, 1.0) | 0.28 |
| PulsePen diastolic BP, mm Hg                       | 78 ± 9     | 76 ± 9      | 0.60      | –1.2 (–3.5, 1.1) | 0.30 |
| Pulse wave analysis                                |            |             |           |                  |                      |
| SphygmoCor carotid systolic BP, mm Hg              | 116 ± 15   | 120 ± 13    | 0.27      | 3.7 (0.4, 7.1)   | 0.03 |
| PulsePen carotid systolic BP, mm Hg               | 126 ± 16   | 0.11        | –5.7 (–7.8, −3.5) | <0.001 |
| SphygmoCor radial AI, %                            | 74.0 ± 13.8| 0.09        | 4.8 (–1.5, 11.0) | 0.13 |
| PulsePen radial AI, %                              | 82.5 ± 11.1| 81.4 ± 19.6 | 0.79      | –3.0 (–9.1, 3.2) | 0.34 |

Values are means ± SD and absolute differences with 95% confidential intervals in parenthesis. Abbreviations: AI, augmentation index; BP, blood pressure; SBP, systolic blood pressure.

¹P value for interclass comparison between A-Pulse and reference.

²P value for absolute difference between A-Pulse and reference vs. zero.
Comparison of Tonometry Devices

measured before tonometry were compared between devices, and no significant difference was found, the measuring time of PulsePen was almost as twice as that of SphygmoCor. This might also have an impact on hemodynamic conditions of participants during measurement, and hence contribute to the unexpected discrepancies in FFs.

Because no significant difference in the interclass comparison between SphygmoCor and PulsePen was detected, the 2 devices would be likely to estimate hemodynamic parameters interchangeably in the setting of a population study. Although a significant absolute difference was observed in hemodynamic parameters measured by SphygmoCor and PulsePen, slopes of correlation plots of these parameters were not significantly different from 1, indicating only a systematical disparity between the 2 devices. In other words, although it is clear that the 2 tonometry-based devices were not consistent in measurements of central BP and wave reflections in clinical practice, based on the separate reference systems, the 2

![Figure 2. Correlation and Bland-Altman analysis of carotid SBP between A-Pulse and SphygmoCor or PulsePen (n = 34). Correlation coefficients, regression models, and 95% CI of slopes of the correlation plots are present. Difference indicates values from A-Pulse subtracted by values from SphygmoCor or PulsePen. Correlation coefficients in Bland-Altman analysis are –0.17 (P = 0.36) and –0.39 (P = 0.02) for A-Pulse vs. SphygmoCor and A-Pulse vs. PulsePen, respectively. Abbreviations: CI, confidence interval; cSBP, carotid systolic blood pressure; SBP, systolic blood pressure.](image-url)
devices could probably predict similar CV risk for individuals. For instance, one patient might have a carotid SBP of 125 mm Hg from SphygmoCor and a carotid SBP of 130 mm Hg from PulsePen, but based on separate reference systems, the patient would be likely evaluated as the same level of CV risk. However, this interpretation remains a possible hypothesis and should be further tested in a clinical trial.

**Comparison Between A-Pulse and SphygmoCor or PulsePen**

Because A-Pulse could not provide measurement of carotid AI, radial AI was compared between A-Pulse and SphygmoCor or PulsePen, and no interclass comparison or absolute difference was observed. However, significant absolute differences in central SBP were detected. Furthermore, the slopes of correlation plots were significantly different from 1, indicating that the considerable discrepancy between A-Pulse and SphygmoCor or PulsePen was not systematic. Consequently, even with separate reference systems, estimation from A-Pulse would not be compatible with those from SphygmoCor and PulsePen with regard to CV risk stratification.

**CV Risk Assessment Considerations**

From a practical point of view, a comparison study of different devices needs to assess both correlations and absolute differences. The strong correlation we found in the present study, together with correlation slopes between SphygmoCor and PulsePen being nonsignificantly different from 1, is in favor of a similar ability of the 2 devices in assessing CV risk. On the other hand, the presence of a significant absolute difference represents a major limitation. Specifically, from a clinical point of view, the tonometry technique needs to be refined in order to provide a consistent hemodynamic measurement; however, before that, it is recommended to specify reference value for each device. From an epidemiological point of view, without taking into account the systematic disparity between devices, meta-analysis cannot be performed in different populations, even if their applied devices were equipped with the same technique.

The present study needs to be carefully interpreted within the context of its limitation. First, our study was limited by its small sample size (n = 66), and only half of subjects with A-Pulse measurements participated in Study 2. Second, although the two operators are both experienced experts for each device, operator bias was another issue we considered. However, with 3 tonometry-based devices randomly measured on each participant in his/her signal visit, the statistical power was sufficient for the comparison study. Further studies with larger sample size and likely with the invasive measurements as gold standard are undoubtedly warranted.

In summary, the present comparison study is not designed to determine which tonometry device is more “accurate,” but to investigate the agreement between them in hemodynamic measurement. We found that all the central BP and wave reflection indexes measured by A-Pulse, SphygmoCor, and PulsePen were strongly correlated, but with substantial discrepancies. However, based on separate reference systems, SphygmoCor and PulsePen, but not A-Pulse, may assess a similar CV risk for individuals.

**DISCLOSURE**

The authors declared no conflict of interest.

**REFERENCES**


