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A new noninvasive device for continuous arterial blood pressure monitoring in the superficial temporal artery

K Y Chin¹,⁴ and R B Panerai²,³

¹ Department of Medical Physics, University Hospitals of Leicester NHS Trust, Leicester Royal Infirmary, Leicester LE1 5WW, UK
² Department of Cardiovascular Sciences, University of Leicester, Leicester Royal Infirmary, Leicester LE1 5WW, UK
³ Leicester NIHR Biomedical Research Unit in Cardiovascular Sciences, Glenfield Hospital, Leicester, LE3 9QP, UK

E-mail: kong.chin@uhl-tr.nhs.uk

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Abstract

Continuous recording of arterial blood pressure (ABP) has many applications in cardiovascular physiology, but existing alternatives rely on measurements performed in the fingers or radial artery. Peripheral recordings have significant differences from central ABP regarding the pattern of the waveform and corresponding systolic and diastolic values. To address the need for noninvasive measurements closer to the ascending aorta, a new device was constructed to measure ABP in the superficial temporal artery (STA) using photoplethysmography and the arterial volume clamping technique. The optoelectronic circuitry to generate the photoplethysmogram is contained in a specially designed probe placed over the STA and kept in place with a head frame. The prototype (STAbp) also includes original designs for the pneumatic, electronic, signal processing, control and display sub-systems. A self-calibration feature regularly updates the photoplethysmogram operating point to improve accuracy. The performance of the STAbp was compared against the Finapres in 19 healthy subjects. At rest, the bias (SD) was −23.1 (15.05), −10.8 (13.83) and −12.4 (12.93) mmHg for systolic, mean and diastolic pressures respectively, without significant differences in drift between the two devices. The 99% bandwidth (SD) for the spectral distribution of ABP waveforms was 5.3 (1.46) Hz for STAbp and 6.8 (0.73) Hz for the Finapres (p < 0.01). Handgrip manoeuvre showed a very similar response to the Finapres, including the rapid return to baseline on release. The new STAbp device has considerable potential as a new tool for clinical and research applications.
where continuous recording of more central ABP is advantageous compared to peripheral alternatives.

Keywords: arterial volume clamping, photoplethysmography, Finapres, arterial pulse bandwidth, central arterial blood pressure

Introduction

Continuous recording of arterial blood pressure (ABP) is an essential requirement in many areas of physiology and clinical investigation. Although intravascular, catheter-based measurements are still the gold standard procedure, the introduction of noninvasive alternatives, such as the Finapres® and radial artery tonometry (Steiner et al 2003), provided a considerable impetus to research activity in many areas such as studies of baroreceptor sensitivity, dynamic cerebral blood flow autoregulation and pulse wave velocity. A major limitation though is that most available devices perform measurements at the periphery thus leading to differences in ABP waveforms and also systolic and diastolic values when compared to ABP recordings in the ascending aorta or other more central arteries (Nichols and O’Rourke 2005). The most common approaches to obtain noninvasive continuous measurements rely either on arterial volume clamping of the digital artery (e.g. Finapres) or the use of arterial tonometry of the radial artery (e.g. Colin® tonometer). For applications requiring only beat-to-beat values of mean ABP, such as assessments of dynamic cerebral autoregulation, peripheral measurements of ABP are not very problematic since mean values of ABP are not considerably different from central estimates, as confirmed by previous studies (Sammons et al 2007). However, this is not the case of many other applications, such as assessment of baroreceptor sensitivity which ideally involves beat-to-beat estimates of systolic ABP (Westerhof et al 2006) or situations where the morphology of the ABP waveform is relevant, such as estimates of pulse wave velocity or instantaneous flow–pressure relationships of the cerebral circulation (Aaslid et al 2003, Panerai et al 2006). For these, one would need to find an artery that is closer to the ascending aorta, but that could also be compressed externally using either arterial volume clamping or tonometry.

Thiagarajah et al (1979) were one of the first groups to suggest that the superficial temporal artery (STA) could be used for ABP monitoring. They used a Doppler ultrasound flow detector to determine systolic and diastolic values but their system did not produce a continuous waveform. In 1996, Tanaka and Yamakoshi (1996) proposed the use of arterial volume clamping of the STA as a possible site for continuous noninvasive measurement of ABP. Unfortunately their original insight never became commercially available, a blueprint was not disseminated and a systematic validation was never reported. Nevertheless, a recent conference article was presented by the same research group (Nogawa et al 2011), which proposed an improved control technique for ABP estimation, but that was not applied to the STA. For this reason we revived their idea and developed a similar device (STAbp), but based on our own designs for the optical sensors, pneumatic components and other hardware and software components. For ethical reasons, initial validation was performed in comparison with the Finapres. As described below, initial results with this new device are very encouraging and should lead to many new possibilities for investigators in the field of cardiovascular physiology.
Methods

Instrumentation

Figure 1(a) shows the STAbp system diagram. As the name implies, arterial volume clamping, also known as vascular unloading technique, applies external pressure as part of a feedback loop to maintain the volume of a selected artery constant and, by doing so, makes the external pressure a very close approximation of the intra-arterial pressure. Arterial volume is measured by photoplethysmography (PPG) using light emitting diodes and sensors inside a specially designed probe (figure 1(b)), made of brass, which also inflates to compress the STA against the temporal bone. The front end flat surface of the probe is sealed with a white acetal ring by a thin flexible but non-compliant layer of polyethylene to form an inflatable air chamber. When inflated fully without resistance, it forms the shape of a dome with a diameter of approximately 18 mm. However, when the sealed chamber is inflated against the temporal bone, the pressure exerted can then compress the STA to promote unloading of the vascular wall.

The blood volume sensor consists of an infrared emitting diode (IRED) and four photodetectors. The IRED illuminates the tissue with the underlying STA. The photodetectors are placed in a reflectance configuration to measure the scattered and/or reflected infrared light from the tissue. Multiple photodetectors, equidistant to the IRED were used to identify the most probable location of the STA. The photodetectors (SMD2420, Honeywell) have a peak wavelength sensitivity matched to the wavelength of the IRED light source at 880 nm (SME2470, Honeywell).

The probe is fastened onto a specially designed head frame with the front end of the probe fixed on the skin surface (figure 1(c)). The head frame, which is made of aluminium, with the versatility to cater for different head dimensions and STA anatomies, maintains the front end of the probe at a fixed distance over the underlying STA. Four support brackets were incorporated to maintain the position of the head frame relative to the head during continuous ABP monitoring. Each support bracket has a long and slim piece of aluminium plate with soft padding. The soft padding is pressed against the scalp when the brackets are fastened. The large area of padding distributes the pressure evenly on the scalp and hence minimizes discomfort and any risks of tissue ischaemia.

The regulated compressing pressure in the inflatable air chamber is supplied by a micro air compressor (AC0105, Medo). The output from the air compressor is regulated (R-920-10, Airtrol) to produce a constant pressure at 5 psi (≈260 mmHg), which is connected to the inlet of a 3/2 way piezo valve (PS11010-31LR, Hoerbiger-Origa). Low compliance pneumatic tubing is used to connect the probe and the compressed air supply. The air volume in the pneumatic components is kept small to improve the frequency response.

The signal-to-noise ratio of the PPG waveform is improved by low pass filtering at a cut-off frequency of 20 Hz using an eighth order Bessel Sallen-Key configuration.

The compressing pressure in the inflatable air chamber is continuously monitored by a pressure transducer (26PC05SMT, Honeywell). When the STA is compressed to maintain the volume clamping, the pressure transducer also indirectly records the intra-arterial pressure in the STA.

Software control

The STAbp prototype is controlled by a desktop computer using Agilent VEEPro® 6.2 software to allow real time signal processing and continuous ABP recording. Digitization of the input signals is performed with an analogue-to-digital converter with 12-bit resolution (DT300, Data Translation), sampled at 200Hz/channel. The real time ABP waveform can also be displayed
Figure 1. Block diagram of the integrated STAbp prototype device. (a) The STAbp device consists of a blood volume sensor which monitors the arterial blood volume change in the superficial temporal artery to generate the photoplethysmogram (PPG). A regulated pressure subsystem compresses the artery at the required pressure. The STAbp is controlled by a desktop computer effecting hardware and software functions. A servo-feedback control mechanism establishes the volume clamp to allow continuous ABP monitoring. See ‘Methods’ section for detailed description. (b) A photograph of the STAbp probe. The probe consists of an inflatable sealed air chamber built-in with four photodetectors (numbered 1 to 4), arranged equidistantly from an infrared emitting diode at the centre. The front-end surface of the probe is covered with a thin flexible but non-compliant layer of polyethylene, sealed with a white acetal ring. (c) A photograph of the STAbp probe fixed by the head frame on the head of a participant. The positioning of the probe (indicated by a white circle) can easily be achieved due to the versatility of its brackets to cater for different head dimensions and locations of the STA. Additional support brackets with paddings (indicated by white arrows) and overhead hook-and-loop straps are available to immobilize the probe and the head frame against the head during continuous ABP monitoring.
on the screen. Two main functions were implemented corresponding to the open loop procedure (OLP) and the closed loop procedure (CLP) respectively (figure 2(a)). The OLP (figure 2(b)) is activated at each start-up of the ABP monitoring process. The best PPG waveform from one of the four photodetectors is visually selected. The selected PPG is then monitored through a range of compressing pressures which encompasses the systolic and diastolic pressures (figure 3(a)). The PPG pulse with the largest pulsation amplitude is identified automatically and its mean value is computed as the setpoint (SETpt, figure 3(b)). The OLP is completed and the CLP (figure 2(c)) is activated to monitor ABP continuously. The CLP repeats in a loop until the operation of the STAbp is externally terminated to end the continuous ABP monitoring.
A subfunction labelled \textit{SETpt Self-Update} is also part of CLP. The subfunction is activated from time to time to maintain the accuracy of the PPG SETpt. The time interval between consecutive SETpt re-evaluations is dependent on the absolute percentage change between consecutive SETpt estimations. The default timer duration is 10 s. If the absolute difference in percentage is within 10\%, the timer duration is increased at 5 s steps. Otherwise, it is reset to its default.

\textit{Subjects and measurements}

Nineteen healthy subjects were recruited (ten males), age (mean \(\pm\) SD) 34 \(\pm\) 12 years old. All participants were staff members of the department. The study was approved by the local ethics committee and written consent was given by each participant.

Each subject was asked to sit comfortably upright on a chair with back support in a temperature controlled (22 \(^\circ\)C) laboratory. The right STA was first located by palpation before the head frame was fixed against the scalp with the front end of the \textit{STAbp} probe positioned on the STA. An appropriate Finapres cuff size was selected and fitted onto the right middle finger. The subject was asked to relax and breathe normally during measurements. The height difference between the STA and the finger artery was taken into account to offset the hydrostatic pressure difference.

Once both devices showed stable waveforms, self-calibration was switched off and resting ABP waveforms were recorded for 3 min. This was followed by another cycle of self-calibration.
on and then off, and then recording of the isometric handgrip exercise at 30% maximal voluntary compression. The handgrip exercise was performed by compression of a partially inflated sphygmomanometer cuff with pressure monitored with an aneroid pressure gauge. After 2 min, subjects released the grip suddenly and the rapid return of ABP to baseline level was monitored. The ABP waveforms were continuously recorded for another 1 min before measurements were terminated in both devices.

Prior to analysis, the recorded ABP waveforms were visually assessed. Considering that only healthy subjects were used, waveforms with pulse pressure of less than 30 mmHg were excluded. Waveforms with unclear systolic peak and diastolic trough were also excluded.

Comparison of the STAbp device in relation to the Finapres was based on five separate sets of parameters, namely:

Resting ABP

To assess the difference in resting ABP, 16 cardiac pulses at the beginning of the 3 min recording were retrieved for analysis. Systolic, mean and diastolic pressure values (SBP, MBP and DBP respectively) were produced from each waveform and averaged.

Assessment of drift

To quantify drift, the difference between percentage changes in the paired ABP waveforms was calculated separately for the STAbp and Finapres using 16 cardiac cycles at the beginning of the recording and same number of beats at the end of the 3 min recording.

ABP bandwidth

Discrete Fourier transform was used to obtain the power spectrum of the same 16 paired ABP pulses selected from the beginning of the baseline recording. The beginning and end of each pulse were smoothed to overcome the discontinuity of the pulse waveform to minimize spectral leakage (Bendat and Piersol 1993). A normalized cumulative power spectrum for the ABP pulse was then computed and the 99% power bandwidth limits were identified using linear interpolation between discrete frequency harmonics.

Frequency response and magnitude squared coherence

Transfer function analysis was used to assess the waveform similarity between the two devices using the Finapres signal as input and STAbp as output. To improve the quality of estimates, auto- and cross-spectra were first computed from individual fast Fourier transform of 16 windowed ABP waveforms segments and then averaged. Each window of ABP waveform consists of 512 sample points, corresponding to 2.56 s, multiplied with a 20% cosine-tapered Hanning window. The Welch method was adopted with 50% overlap between windows. Smoothed auto- and cross-spectral estimates were then used to obtain the squared coherence function, amplitude and phase frequency responses.

Isometric exercise

Changes in ABP due to handgrip were quantified by the percentage change from baseline (ten cardiac cycles before handgrip) to the end of the manoeuvre (ten cardiac cycles before release) for SBP, MBP and DBP.
Statistical analysis

Analysis of agreement (Bland and Altman 1986) was adopted to evaluate relative performance of the STAbp in comparison with the Finapres. For all parameters extracted above, the bias was calculated by the mean of individual differences between the STAbp and the Finapres values. The limits of agreement correspond to $\pm 1.96 \cdot SD_d$ where $SD_d$ is the standard deviation of differences. Paired Student’s $t$-tests were used to test differences between means, including the percentage drift for the two devices. Pearson’s correlation coefficients were adopted to test trends in Bland–Altman plots. Statistical significance was accepted for $p < 0.05$.

Results

Figure 3 gives an example of recorded transducer pressure and PPG waveforms during the process of determining the SETpt. The dashed box illustrates the identification of the largest PPG pulsation which determines the SETpt.

Visual inspection of resting ABP recordings led to the rejection of three subjects due to poor ABP waveforms, in two cases related to instability of the SETpt. Hence, only the remaining 16 subjects’ recordings of resting ABP were analysed. During the isometric handgrip exercise, another two subjects were rejected for similar reasons.

ABP waveforms for the Finapres and STAbp are shown in figure 4 for 16 cardiac cycles at the beginning and end of the 3 min recording respectively.

Table 1 presents the average absolute resting ABP values (SD) and the corresponding biases ($SD_d$) for SBP, MBP and DBP. The respective Bland–Altman plots of agreement are shown in figure 5. Paired $t$-tests showed significant differences for SBP, MBP and DBP ($p < 0.001$, $p < 0.01$ and $p < 0.01$ respectively). Linear regression analysis of differences
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Table 1. ABP recordings at rest. All values given in mmHg.

<table>
<thead>
<tr>
<th></th>
<th>SBP</th>
<th>MBP</th>
<th>DBP</th>
</tr>
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<tbody>
<tr>
<td>Finap</td>
<td>113.4 ± 9.26</td>
<td>75.7 ± 5.54</td>
<td>57.5 ± 5.39</td>
</tr>
<tr>
<td>STAbp</td>
<td>90.4 ± 17.32</td>
<td>64.9 ± 14.32</td>
<td>45.1 ± 12.42</td>
</tr>
<tr>
<td>Bias</td>
<td>−23.1 ± 15.05</td>
<td>−10.8 ± 13.83</td>
<td>−12.4 ± 12.93</td>
</tr>
<tr>
<td></td>
<td>(p &lt; 0.001)</td>
<td>(p &lt; 0.01)</td>
<td>(p &lt; 0.01)</td>
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</table>

Average absolute ABP values (± SD) for each test computed for SBP, MBP and DBP between Finapres and STAbp and the corresponding bias ± SD.
ABP, arterial blood pressure; SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure.

Table 2. Parameters adopted to compare drift and the response to the isometric handgrip exercise.

<table>
<thead>
<tr>
<th></th>
<th>SBP</th>
<th>MBP</th>
<th>DBP</th>
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<tbody>
<tr>
<td>DFinap (%)</td>
<td>−0.8 ± 6.43</td>
<td>−1.5 ± 6.00</td>
<td>−2.2 ± 6.60</td>
</tr>
<tr>
<td>DSTAbp (%)</td>
<td>1.0 ± 7.16</td>
<td>0.9 ± 7.79</td>
<td>−0.1 ± 9.00</td>
</tr>
<tr>
<td>HFinap (%)</td>
<td>10.5 ± 11.81</td>
<td>14.1 ± 12.34</td>
<td>15.8 ± 14.20</td>
</tr>
<tr>
<td>HSTAbp (%)</td>
<td>10.3 ± 9.69</td>
<td>11.8 ± 10.45</td>
<td>11.3 ± 11.21</td>
</tr>
</tbody>
</table>

Percentage changes in ABP for SBP, MBP and DBP between STAbp and the Finapres. Values are shown as the mean ± SD. No significant differences were detected between DFinap and DSTAbp, and between HFinap and HSTAbp.
ABP, arterial blood pressure; SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure; Finap, Finapres reference device; STAbp, prototype device; D, percentage change in resting ABP for Finapres or STAbp; H, percentage change in ABP during isometric handgrip exercise for Finapres or STAbp.

Discussion
Main findings
A new device to perform continuous noninvasive measurements of ABP in the temporal artery (STAbp) was able to provide comparable ABP waveforms to the Finapres device, without significant differences in beat-to-beat dynamic response to isometric exercise or drift against the mean pressures (figure 5) showed significant correlations of 0.61 (p < 0.02), 0.75 (p < 0.01) and 0.69 (p < 0.01) for SBP, MBP and DBP respectively. However, no significant correlation was detected between subjects’ ABP differences with age.

The 99% bandwidth (SD) was also significantly different between the two devices (p < 0.01) with the STAbp reaching 5.3 (1.46) Hz and the Finapres 6.8 (0.73) Hz respectively.

The gain, phase and coherence frequency response curves for the transfer function between the Finapres and STAbp waveforms are given in figure 6. The mean gain frequency response shows a cut-off frequency (~3 dB) at approximately 3 Hz, followed by a return to higher values above 9 Hz. Phase shift is negligible until about 3.2 Hz when it gradually increases before stabilizing from approximately 9.5 Hz. Mean coherence remains elevated (>0.5) up to at least 12 Hz.

Measures of drift and response to isometric exercise did not show any significant differences between the STAbp and the Finapres (table 2), indicating that the two devices had relatively small percentage drift in the same direction. Correlation coefficients for the differences in Bland–Altman plots were also non-significant. During the isometric exercise, simultaneous variation of the ABP can be observed in both recording devices as depicted in figure 7. This characteristic pattern of response to isometric exercise, including the sudden drop at release, was observed in all subjects.

Discussion
Main findings
characteristics. On the other hand, the frequency response of the new device was inferior to the Finapres, as reflected by the 99% power bandwidth and the transfer function characteristics between waveforms from the two devices. Moreover, for resting values there were significant biases for SBP, MBP and DBP. For SBP it is likely that the higher values observed in the finger were partially due to the pulse amplification phenomena resulting from wave propagation from the ascending aorta to the digital artery (Nichols and O’Rourke 2005). From the MBP and DBP though, there is the suggestion that the STAbp underestimates ABP by approximately 10 mmHg in comparison with the Finapres. MBP and DBP tend to be relatively constant across the arterial tree (Nichols and O’Rourke 2005), but it is not possible to ascribe all the
Figure 6. Spectral characteristic curves. (a) The average gain spectrum shows a cut-off frequency at approximately 3 Hz (indicated by dotted lines). (b) Average phase spectrum remains fairly stable up to about 3.2 Hz and gradually increases before stabilizing at approximately 9.5 Hz. (c) Average magnitude squared coherence remains above 0.5 even beyond 12 Hz (dotted lines). The error bars are ±1SD for respective frequencies.

bias (~10 mmHg) to the STAbp since the Finapres itself can have a limited accuracy (Chin and Panerai 2012, Imholz et al 1998, Sammons et al 2007).

A relatively large number of studies have shown that the Finapres itself does not provide reliable values of ABP at rest (Imholz et al 1998), but does provide an excellent correlation with dynamic changes in ABP, for example in response to tilting, exercise, Valsalva and other manoeuvres. Whilst these characteristics of the Finapres present a limitation to the assessment of bias for measurements at rest, it suggests that the STAbp device might be equally suited
Figure 7. Representative recording of SBP, MBP and DBP during isometric handgrip exercise from a 23 year-old female subject. The beat-to-beat arterial blood pressure with STAbp (black continuous lines) and Finapres (grey continuous lines) are shown for SBP (diamond), MBP (solid square) and DBP (triangle). The vertical lines indicate the beginning and end of the 2 min handgrip exercise. When the hand grip was released at the end of the 2 min, a clear dynamic drop in arterial pressure can be observed. SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure.

Areas where STAbp would be particularly advantageous would be dynamic measurements of ABP during changes in head height, like tilting or sit-to-stand manoeuvres in conjunction with studies of cerebral haemodynamics.

Characteristics of the STAbp device

ABP measurements derived from the STA might have several advantages compared to other alternatives like the finger, but one inherent difficulty is the exact location and orientation of the STA. To minimize this problem, four photodetectors were fitted inside the probe, although only one photodetector can be used at any one time. This design offers the advantage to search the location of the STA with more confidence based on the quality of the PPG waveforms before continuous ABP monitoring begins.

After recordings that lasted approximately an hour, none of the participants reported any signs of headache, pain, dizziness or other discomfort. The design adopted for the head frame (figure 1(c)) proved very successful for most participants (but not all as discussed below), by providing sufficient grip against the scalp and well distributed contact pressures on the tissue away from the STA.

The STA is a terminal branch of the external carotid artery with a mean outside diameter (SD) of 2.1 (0.14) mm (Czerwinski 1992). Ten variations of the STA anatomy were documented but without significant differences between male and female subjects (Marano et al 1985, Stock et al 1980). A large majority of subjects has STA that gives rise to two terminal branches 3 to 5 cm above the zygomatic arch, i.e. the frontal and parietal branches. The frontal branch
of the STA anastomoses with other anterior arteries, whereas the parietal branch anastomoses with the contralateral and the posterior arteries. Perfusion of extra-cranial tissues with this complex vascular network, which includes ample collateral blood supply, reduces concerns regarding venous congestion or ischemia if there is prolonged compression of one of the STA (Bergersen 1993). These characteristics of the STA are important to appreciate differences from arterial volume clamping measurement in the finger.Whilst the Finapres and similar devices detect beat-to-beat volume changes of the digital artery by optical transmission, in the STA this needs to be done by reflection of the light by the temporal bone and surrounding tissues. As a consequence, a number of variables can cause differences between the two types of measurements, such as tissue elasticity, local vasomotor activity, prevalence of anastomoses and temperature regulation. Technical design parameters are also likely to be influential, such as the area and mode of compression (concentric versus unidirectional), hardware configuration and signal processing algorithms.

Limitations of the study

The main limitation of our study is the use of the Finapres as the reference for evaluation of the new STAbp device. This was part of a two-stage process since direct evaluation against intravascular, catheter-based measurements was not deemed ethical before it could be demonstrated that the new device performed satisfactorily in comparison with an existing noninvasive commercial alternative. Following the results of this study, direct comparison with intravascular measurements are warranted, but it is important that these are performed in the ascending aorta, to minimize any differences due to wave propagation and reflection as could be expected in the radial or brachial arteries.

Differences between SBP, MBP and DBP values of the STAbp device and corresponding values from the Finapres were not random in relation to the average from the two devices (figure 5), but showed a positive correlation. This behaviour may be caused by non-uniform compression of the temporal probe with increasing values of ABP.

The difficulty of obtaining acceptable data in all subjects is also of concern. Physiologically meaningful recordings could not be obtained in three subjects at rest and five subjects during the isometric handgrip. The main reason for this difficulty is likely to be the head frame used to hold the probe. In this initial evaluation we used a ‘one-size-fits-all’ approach resulting in a metallic ring-shaped structure that was much larger than some subjects’ heads. As a result, fixation of the probe was sometimes precarious and stability during inflation of the probe may be compromised. In some participants, this mismatch between head shape and geometry of the head frame might have also contributed to a loss in signal quality due to movement. From the lessons learned, the use of customized head frames, based on three or four different sizes, is likely to result in substantial improvements.

Given that the subjects recruited were all relatively young and healthy, these initial results should not be extended to other age groups or patients with a range of conditions that may affect their peripheral circulation. Nevertheless, since ageing increases arterial stiffness and conditions such as diabetes and Raynaud’s disease can impair peripheral blood flow control, there are many situations where measurements in the STA might be more accurate or preferable than in the finger.

Further work

In the current design of the STAbp, the best PPG waveform from one of the four photodetectors is manually selected after visual inspection. It is our aim to automate this selection process in
the future version of the device. Prior to that, further work may be required to collect a wider range of waveform morphologies to be set as the benchmark.

Further optimization of the surface area of compression from the front end of the probe on the STA could be useful to improve the effectiveness of pressure transmission. This could be carried out in conjunction with exploring different arrangements for optoelectronic and pneumatic components. The use of mathematical modelling or a suitable experimental test rig would also allow for separate quantification of different factors that can affect performance, such as the optical properties of the artery, the surrounding tissue and the skull bone at the temporal region, and other factors that could influence the PPG waveshape. This further work will also help to identify the cause(s) for the non-random distribution of differences in ABP (figure 5), and that the combined head frame and probe subsystem are able to provide uniform compression on the STA across the required ABP range.

The frequency response of the $STA_{bp}$ could be improved in order to provide a flat frequency response over the bandwidth of interest. This could be achieved by using a filter equalization technique in hardware and/or software to recover a flat response to maintain the fidelity of the ABP waveform pattern, mainly in applications where time intervals or derivative functions are the main interest such as pulse wave velocity or pulse contour analysis.

Anatomical and physiological considerations indicate that ABP measurements in the STA should provide a better approximation to central ABP than corresponding measurements in the finger or radial artery, for example by tonometry. Nevertheless, the use of generalized transfer functions, similarly to what has been adopted for more peripheral measurements (Martina et al. 2012) could be envisaged to improve estimates of central ABP from measurements in the STA. Moreover, it could also be argued that these might be less sensitive to the influences of age, gender and pathological conditions (Hope et al. 2002, 2007, 2008) than those derived from measurements in the finger or radial artery.

The initial validation of the $STA_{bp}$ device against the Finapres provided encouraging results that warrant further validation against intravascular measurements, ideally in the ascending aorta. Successful validation in comparison with an intravascular catheter-tip transducer in the ascending aorta must be followed by wider evaluation to include different age groups and patients with different conditions, particularly those with increased arterial stiffness or other pathologies that might affect the difference between peripheral and central measures of ABP.

**Conclusion**

A prototype device that can measure continuous ABP by noninvasive means in the STA has been constructed and validated against the well known Finapres device. The new device can be useful in studies requiring measurements of central blood pressure, or protocols involving changes in posture when there is interest in monitoring cerebral perfusion pressure. Furthermore, it could also be an alternative for individuals that cannot have noninvasive measurements in the fingers, due to pathology or, in the case of premature neonates, due to the non-existence of finger probes of the appropriate size. Further validation is required in older subjects and patients with cardiovascular conditions.

**Acknowledgments**

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